Chem Ed

EDITORIALLY SPEAKING

Re-examination of ideas previously taken for granted is one of the most productive and at the same time exciting ways of becoming educated. Sometimes ideas turn out to be of so little use that we discard them as "wrong." (Farewell, phlogiston!) Other times we find how much an idea has gained in utility and importance. New techniques have contributed information from areas we thought to be far removed or at best peripheral. In either case, we see a little more of nature's unity.

The idea of atomic weights has been a part of chemistry since the time of Dalton. In modern times it has been accorded the prestige of a museum piece. We recall hearing the author of a recent paper on chemical atomic weight determination refer to himself as a "dinosaur." Most of us take the numbers we find on the textbook flyleaf for granted, or at most give a polite historical nod to Berzelius' suggestion of 100 for the oxygen value. Refinements we expect. They show up mysteriously every few years with the authority of the IUPAC Commission on Atomic Weights behind them.

The current concern for establishing a unified scale of atomic weights and nuclidic masses takes in much more than a review of published information and an evaluation of reliability of measurement. The utter simplicity of the problem—choice of a single reference substance and assignment of a numerical value to its relative mass—means that the very fundamentals of all physical science are involved. As is true of all important problems, it is bound to involve a synthesis of information from diverse fields of investigation.

No chemistry teacher can afford to let this part of the scientific world pass by unnoticed. Fortunately he has available an account of the problem set forth in some of the most lucid scientific writing we have ever read. We refer to the reports by Edward Wichers, associate director of the Bureau of Standards and president of the IUPAC Commission on Atomic Weights (see *J. Am. Chem. Soc.*, **78,** 3235 (1956), **80,** 4121 (1958); *Chem. Eng. News*, June 9, 1958, p. 70, Sept. 8, 1958, p. 76; *Phys. Today*, Jan. 1959, p. 28).

There are obvious historical overtones. The choice of oxygen as a reference element won out over the advocacy of hydrogen by the Prout hypothesis followers. A century later the monumental work of Morley, Noyes, and Richards not only established values but also demonstrated the investigative power of chemical stoichiometry. No teacher of analytical chemistry can let his student be unaware of this debt.

Fusion of chemical and physical lines of attack on the problem of weighing an atom occurred as soon as the mass spectrograph become a reliable tool. Aston's pioneering work suggested that the data of isotopic masses needed only equally accurate data on relative abundances to substantiate fully the established chemical atomic weight scale. However, the issue soon was beclouded by the very genii from the lamp he rubbed, isotopes. Evidence from optical spectra showed that Aston's reference substance was a mixture of oxygen isotopes. Since that time the increased accuracy both in the measurement of isotopic masses and in the relative abundance of O^{16}, O^{17}, and O^{18} have made the "chemist's 16" untenable to the physicist. His instruments accurately measure mass ratios and tell him not only that the "chemist's 16" ought more nearly to be defined as 15.9956 but that it is variable!

Here a reasonable solution dictated by logic and one dictated by practicality collide head-on. Abandonment of the chemist's scale for another differing by a factor this large (3 parts in 10,000) would mean that at least a million data of precision better than this now recorded would have to be found in the literature and corrected.

The chemist who follows the story from here on will learn much about the methods the physicist uses. In a search for a compromise scale, various reference substances have been proposed. Chemists would be willing to give the anisotopic element fluorine the assigned value 19. This would require a shift of only 1 part in 25,000 and have the attraction of a stoichiometrically useful reference atom. Physicists, however, would have the frustration of trying to calibrate their instruments against a standard with an assigned prime number.

The nuclide which now seems to be leading the pack is C^{12}. This may surprise chemists who have not learned the experimental problems of the physicist. Reassignment of values would modify present figures by about 4 parts in 100,000 downward. Obviously *all* atomic weight values would be involved so that no gravimetric factors would be changed.

When can a decision on this important matter be expected? Possibly next summer. Meantime chemistry teachers should get out ahead of their textbooks. As is usually the case, by doing so they will be sure to gain a better appreciation of what is in the ones they are using now.

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Foundations of the Structural Theory

One hundred years ago the simple concepts of the structural theory were published by two young chemists, August Kekulé (*1*) and Archibald Scott Couper (*2*). Working entirely independently, each had arrived at an understanding of the tetravalence of carbon and the self-linking of carbon atoms. With these simple concepts they brought an end to the "Age of Confusion" of organic chemistry.

For several decades chemists had been seeking some principle to provide a basis for understanding organic substances and their reactions. Polemics raged as opposing schools advanced conflicting proposals. Once presented, the structural theory provided so simple, and, yet, so useful an interpretation of organic substances and their reactions that it quickly converted most of the disputants (*3–5*).

At once the chains restraining the progress of the science were ruptured. In contrast to the slow empirical progress of previous years, organic chemical research bounded ahead.

From the structures of the simple saturated derivatives, chemists progressed to an understanding of unsaturated compounds with multiple carbon-to-carbon bonds. Next the structures of benzene and related organic molecules were worked out. In 1874 van't Hoff accounted for the existence of optical isomers in terms of a tetrahedral configuration of the carbon atom. Thus, within sixteen years of the original proposal of the structural theory, all of the basic concepts had been advanced.

Today we discuss the chemistry of hundreds of thousands of organic molecules in terms of their structures. We interpret the behavior of high polymers in terms of their molecular constitution and configuration. We interpret the behavior of drugs in terms of their molecular dimensions and shapes and their ability to occupy molecular sites of related shape requirements in biological systems. Finally, we are making active progress in unraveling the structures of those amazing, versatile polymers of life—the proteins.

One hundred years of structure—one hundred years of amazing progress! We owe a real debt of gratitude to the two young chemists who first pointed the way to this magnificient highway of chemical investigation. It is fitting that we commemorate their contribution and honor their memory.

When I was invited to join with the various Divisions in this honor to Kekulé and Couper, I accepted with pleasure. All of us, active in research today, owe a deep debt of gratitude to these two pioneers. However, when I considered the precise form that my tribute should take, I found my decision less easy.

One possibility was to discuss recent triumphs and present problems. It is always pleasant to review an area of research in which one has direct, active interests.

The Kekulé-Couper Centennial Celebration commemorating the pioneering papers by F. A. Kekulé and A. S. Couper on the tetravalence and self-linking of carbon atoms was held on September 10, 1958, at the Chicago Meeting of the American Chemical Society. In the morning a symposium on the Development of Theoretical Organic Chemistry was held under the auspices of the History of Chemistry Division. Papers presented at the symposium will appear in forthcoming issues of THIS JOURNAL.

In the afternoon, Herbert C. Brown, Professor of Chemistry at Purdue University, delivered the Kekulé-Couper Centennial Lecture before the Divisions of Chemical Education, History of Chemistry, and Organic Chemistry. For many years the lecturer has had an active interest in the history of chemistry. He has, in addition, made major contributions to the theory of organic chemistry, contributions that are in direct line of descent from the papers this lecture commemorates.

In fact there exists a close parallelism between the period in which Professor Brown initiated his researches into steric effects and the period preceding the enunciation of the structural theory. Both periods were characterized by the dominance of an electrochemical theory. In the 1830's Berzelius' dualistic theory of chemical combination was decisively challenged by the demonstrations of Dumas and Laurent that replacement of hydrogen by chlorine did not greatly alter the chemical characteristics of many compounds. In the 1930's a highly successful electronic theory seemed likely to explain by electrical concepts almost all chemical effects of atoms or groups.

The development by Professor Brown of a quantitative method for estimating the magnitude of steric strains made possible a new understanding of the importance of the steric factor in chemical behavior. Herbert Brown was, of course, not alone in re-emphasizing nonelectrical factors. Bartlett, Ingold, Newman, Westheimer, and many others have contributed to our present understanding of steric effects. Undoubtedly, however, Herbert Brown deserves major credit for rescuing steric concepts from the disrepute into which they had generally fallen, and for re-establishing them as factors of great significance in the total understanding of organic chemistry. Therefore, it is particularly appropriate to have Professor Brown participate in this tribute to the founders of the structural theory.

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A second possibility was to trace the course of development of the structural theory from its original proposal to its highly developed stage today. One hundred years of structural chemistry—a truly stirring story of success in chemistry and a most inspiring topic for a lecture! Finally, there was the possibility of reviewing the confusing background against which the structural theory made its appearance. This period has been reviewed in various histories of chemistry (*3–5*) and was thoroughly treated in Japp's magnificant Memorial Lecture to Kekulé (*6*). Such a review offered little possibility for a truly original contribution.

However, after careful deliberation, I turned away from the temptations of the first two possibilities and adopted the last. I was influenced in this decision by the following considerations.

The Lessons of History

Little attention is paid to the history of chemistry in our graduate schools today. In part, this is the result of an ever growing, ever more crowded curriculum; in part, it arises from the great youth and vigor of chemical research in America. Let us go back a mere 25 years. The state of organic chemistry in this country may be indicated by pointing out that not a single advanced organic chemistry textbook, originating in the United States, was then available. Not until 1937 did the first such book, by Frank C. Whitmore, appear (*7*).

These 25 years have witnessed a remarkable upsurge of organic chemistry in this country. Chemical research is being pursued with vigor and intensity. It is a recognized characteristic of youth to ignore the past. And the history of chemistry has been ignored. Little attention is paid to the lessons that history can teach.

An incident at the last Organic Symposium illustrates the point. At that time I made the statement that a sound principle to adopt in chemical research is that chemistry is *simple*, and *appears* complicated only when the experimental data are poor or when the currently accepted theory used to account for the data is unsatisfactory. This position appeared to amuse the audience. Yet it can be supported by numerous examples from the chemical history.

There appears to be at the present time a tendency to glorify the importance of empirical observations and to expect that any new theory should account immediately for all experimental observations on record. This ignores the lesson that a considerable fraction of experimental observations made without the benefit of the careful scrutiny provided by a sound theory has invariably turned out to be erroneous in the past. Consequently, the worker who proposes a new theory or interpretation must attempt to separate the apparently sound and consistent data from other results which fail to fit the proposed theory. These results must then be re-examined experimentally in order to test the new theory.

This has been the course of theoretical developments in the past. There is no reason to anticipate that it will not be the course in the future.

Unfortunately, our present graduates in chemistry have had so little contact with the lessons of chemical history that this view is foreign to them. We have numerous textbooks available today which give the present position of chemical hypotheses and theories. Such textbooks point out the various facts that these theories satisfactorily interpret. They fail to review the difficult and tortuous paths which led to the present positions. Not a single advanced textbook which I examined even mentioned the background against which the structural theory was proposed. Consequently, I decided that I should be rendering a service to the younger chemists of today, as well as giving a proper tribute to Kekulé and Couper, by emphasizing once again these important lessons of history, illustrated by the origins of the structural theory.

The Age of Confusion: Background for Structural Theory

Let us then briefly review the background against which the contribution made by Kekulé and by Couper in 1858 appeared. In 1808 Dalton proposed his atomic theory (*8*), and a rapid development of chemical theory based on this important contribution might have been anticipated. Unfortunately, this was not realized. Chemical theory rapidly degenerated into a morass of confusion, so that some eminent chemists such as Liebig expressed disgust at the state of theory and retired to the simpler problems of practical and applied chemistry.

The half century preceding the foundation of the structural theory in 1858 is the "Dark Age of Organic Chemistry," an "Age of Confusion," with numerous currents and counter-currents, violent polemics, and relatively little progress (*3–5*).

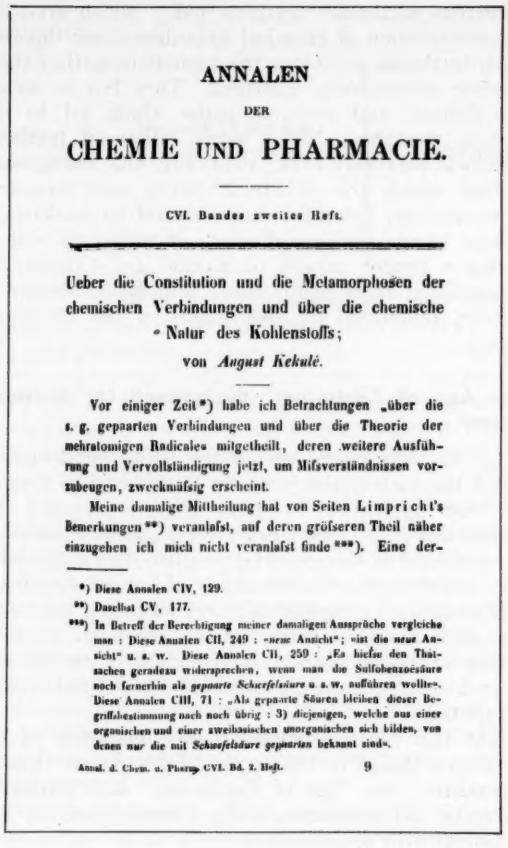
On the practical side, a number of important advances were made. Organic analysis became precise. Methods of separation became refined. Numerous organic substances were isolated, analyzed, and characterized. Acids, such as acetic, butyric, stearic, tartaric, and succinic were recognized materials. Fats were shown to be composed of fatty acids and glycerol. Alkaloids such as morphine, strychnine, brucine, and quinine were isolated and characterized.

The difficulty arose in attempting to proceed from the analytical results to a molecular formula. Considerable confusion existed as to the correct atomic weights. At various times carbon was assigned a weight of 6 and oxygen 8 (on the basis of hydrogen equal to 1). At other times, the accepted values were carbon 12 and oxygen 8, or carbon 6 and oxygen 16. Still others championed the present values, but with most of the metals having half the present atomic weights.

It is highly unfortunate that this confusion existed, since all of the tools were at hand to construct a con-

The Cover

The Kekulé-Couper Centennial commemorates the papers on the tetravalence and chain-forming capacity of carbon atoms. The titles of the two papers (KEKULÉ, *Ann.*, **106**, 129 (1858); Couper, *Compt. rend.*, **46**, 1157 (1858)) are reproduced together with photographs of the same period. Source of Kekulé photo: Fig. 56, p. 233, in RICHARD ANSCHÜTZ, "August Kekulé," Vol. I, Verlag Chemie, Berlin, 1929.



ANNALEN

DER

CHEMIE UND PHARMACIE.

CVI. Bandes zweites Heft.

Ueber die Constitution und die Metamorphosen der chemischen Verbindungen und über die chemische Natur des Kohlenstoffs;

von *August Kekulé*.

Vor einiger Zeit*) habe ich Betrachtungen „über die s. g. gepaarten Verbindungen und über die Theorie der mehratomigen Radicale« mitgetheilt, deren weitere Ausführung und Vervollständigung jetzt, um Mifsverständnissen vorzubeugen, zweckmäfsig erscheint.

Meine damalige Mittheilung hat von Seiten Limpricht's Bemerkungen**) veranlafst, auf deren gröfseren Theil näher einzugehen ich mich nicht veranlafst finde***). Eine der-

*) Diese Annalen CIV, 129.

**) Daselbst CV, 177.

***) In Betreff der Berechtigung meiner damaligen Aussprüche vergleiche man: Diese Annalen CII, 249: »neue Ansicht«; »ist die neue Ansicht« u. s. w. Diese Annalen CII, 259: „Es hiefse den Thatsachen geradezu widersprechen, wenn man die Sulfobenzoesäure noch fernerhin als *gepaarte Schwefelsäure* u. s. w. aufführen wollte«. Diese Annalen CIII, 71: „Als gepaarte Säuren bleiben dieser Begriffsbestimmung nach noch übrig: 3) diejenigen, welche aus einer organischen und einer zweibasischen unorganischen sich bilden, von denen nur die mit *Schwefelsäure gepaarten* bekannt sind«.

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sistent scale of atomic weights. In 1808 Dalton had proposed that the chemical elements were composed of small, ultimate particles which retained their identity in chemical reactions. All of the ultimate particles of a given element were identical. He stressed the importance of proceeding from analytical data to a determination of the relative weights of these particles and to their numbers in the molecules of various substances. In 1811 Avogadro clearly distinguished between the atom and the molecule of an element and pointed the way to the determination of atomic and molecular weights by comparing the densities of gases (*9*). Unfortunately some cases of dissociation led to apparent anomalies and to the consequent abandonment of his proposal, so that only after 1858 was it finally adopted as a result of Cannizzaro's clear exposition of its merits (*10*).

A second major difficulty was the general acceptance of the "dualistic system" of Berzelius. Impressed by the electrochemical results of Davy, he carried out simple experiments in which he observed the simultaneous formation of an acid and a base in the electrolysis of various salts. Consequently, he concluded that chemical combination must be an electrical phenomenon. His view is expressed in the following quotation (*11*).

If these electrochemical views are correct, it follows that all chemical combination depends solely on two opposing forces, positive and negative, and that each combination should be composed of two parts united by the effect of their electrochemical reaction, provided that there exists no third force. Whence it follows that each compound substance, regardless of the number of its constituent principles, may be divided into two parts, of which one is electrically positive and the other negative. Thus, for example, sulfate of soda is not composed of sulfur, oxygen and sodium, but of sulfuric acid [SO_3] and soda [NaO] which both may again be divided into two elements, one positive and the other negative.

The confusion introduced by this combination of erroneous (and variable) atomic weights, indefinite molecular weights, and the interpretation of composition in terms of the dualistic system may be understood by examining the representation of calcium acetate, acetic acid, ethyl alcohol, and ethyl ether (*5*).

Since a salt is a combination of the metal oxide and the acid, calcium acetate, $C_4H_6O_4Ca$ (C = 6, O = 8), must be represented as $C_4H_6O_3 + CaO$. Therefore acetic acid must be $C_4H_6O_3$. (The fact that glacial acetic acid contains one more molecule of water than required by this formula was ignored.) Since acetic acid can be obtained by oxidation of ethyl alcohol, the latter was written $C_4H_{12}O_3$. Ethyl ether arises from the dehydration of ethyl alcohol. Its composition was represented as $C_4H_{10}O$.

The study of ammonium salts had earlier led to the idea of a radical, ammonium, which could perform the functions of a metal. Consequently, it was a natural step to seek to analyze the composition of these oxygen compounds further into a combination of a hydrocarbon radical and oxygen. At different times the derivatives of ethanol discussed previously were postulated to be composed of the etherin radical, C_4H_8, the ethyl radical, C_4H_{10}, or the acetyl radical, C_4H_6. Originally, it was assumed that these radicals, like the metals they were supposed to resemble, could exist in the free state.

Apparently, we owe to a development in industrial chemistry the immediate experimental developments which resulted in the overthrow of this approach to organic chemistry. It is reported that at an important social function in Paris at the Tuileries, the guests were annoyed by irritating fumes, presumably hydrogen chloride, emitted by the burning candles. Dumas investigated the phenomenon. He discovered that the wax used in the manufacture of the candles had been bleached with chlorine. Thereupon, he proceeded to study the action of chlorine and bromine on various organic compounds.

He soon recognized that it was possible to replace one or more hydrogen atoms in various compounds by an equivalent number of halogen atoms without a marked change in chemical behavior. In 1839 he transformed acetic acid into trichloroacetic acid and noted that the chemical behavior of the two acids was very similar. It was obviously counter to the tenets of the dualistic system that electronegative chlorine should be capable of displacing electropositive hydrogen without significant change in the chemical nature of the product.

Berzelius and his followers attacked vigorously. I feel confident that many have enjoyed reading the satire published by S. C. H. Windler (i.e., "schwindler") in 1840 in which he reports his remarkable results on chlorinating manganous acetate. First he replaces the hydrogens of the acetate groups and observes that the product is similar to the original reactant. Further chlorination replaces the oxygen atoms, then

the carbon, and finally the manganese. He achieves a substance which contains only chlorine but which possesses all the properties of the original manganous acetate (*12*).

In spite of such attacks and ridicule, the fact of substitution could not be dismissed. It required a major change in the formulation of organic compounds and led to the "unitary theory." The molecule was regarded as a unit, parts of it being capable of substitution without alteration of its chemical type. Although organic radicals were soon incorporated into the formulation of compounds, it was generally assumed that these radicals were incapable of independent existence, but were merely assemblages of atoms which were transferred without change from one structure to another in the course of reaction. No attempt was made to inquire into the structure of the radical or into the nature of the forces holding together the assemblage of atoms.

Once the molecule was treated as a unit, certain similarities as to type were recognized. In 1850 Hofmann investigated the amines and showed that they could be formulated as NH_3 in which one, two, or three hydrogen atoms were replaced by a corresponding number of organic radicals. Similarly, Williamson clarified the relationship between water, alcohol, and ether. Finally, in 1857 Kekulé proposed the methane type and pointed out that many simple carbon compounds, such as methyl chloride, chloroform, and chloropicrin, could be simply related to the parent molecule.

One further development must be mentioned at this time. Frankland, an adherent of the old radical theory, undertook to prepare free radicals. He treated ethyl iodide with zinc and obtained a substance which he considered to be free ethyl, apparently providing a powerful support for the radical theory. In the course of this investigation, he isolated the zinc alkyls for the first time, investigated their chemical behavior, and demonstrated their utility in organic synthesis.

During his investigation of organometallics, Frankland became impressed by the observation that the presence of alkyl groups reduced the number of other atoms which combined with the metal atom. In other words, oxygen derivatives of the metal alkyls were not the simple oxides associated with organic radicals; they were the oxides with one or more oxygen atoms replaced by organic radicals. Consideration of this phenomenon led him to the concept of valence. To quote (*13*):

> When the formulae of inorganic chemical compounds are considered, even a superficial observer is impressed with the general symmetry of their construction. The compounds of nitrogen, phosphorus, antimony, and arsenic, especially, exhibit the tendency of these elements to form compounds containing 3 or 5 atoms of other elements; and it is in these proportions that their affinities are best satisfied: thus in the ternal groups we have NO, NH_3, NI_3, NS_3, PO_3, PH_3, PCl_3, SbH_3, $SbCl_3$, AsO_3, AsH_3, $AsCl_3$, etc.; and in the five-atom groups, NO_3, NH_4O, NH_4I, PO_5, PH_5I, etc. Without offering any hypothesis regarding the cause of this symmetrical grouping of atoms, it is sufficiently evident, from the examples just given, that such a tendency or law prevails, and that, no matter what the character of the uniting atoms may be, the combining-power of the attracting element, if I may be allowed the term, is always satisfied by the same number of these atoms.

A half century of confusion—opening on the promising note of the atomic theory of Dalton but closing on a most pessimistic phase. Organic chemists were no longer hopeful of describing the composition of molecules or of ascertaining the forces operating to hold the molecular assemblages together. Their main hope was to recognize simple types which would permit them to predict the results of simple chemical reactions.

Even in this dark age of organic chemistry, all was not black. In A. W. Hofmann's laboratory in London, a young student, W. H. Perkin, undertook to synthesize quinine by the oxidation of an aniline derivative. In terms of the empirical formulas in use at the time, the chemical transformation appeared to be a simple one. In terms of our knowledge of chemical structure, the change is highly improbable, to say the least. Perkin failed to obtain quinine, but he did obtain the color, mauve, and thereby initiated the coal tar dye industry (*14*).

It is certainly a gratifying experince to be able to close one's eyes in an unmarked, unknown wilderness, set out for a specific objective, and stumble across another highly desirable goal. However, such a fortunate occurrence is rare. We are far happier to find ourselves in the midst of a carefully charted area, able to proceed with open eyes to our objective in new uncharted areas with the aid of well-tried theories and methods.

That this is the situation at the present time we owe to the pioneering efforts of Kekulé and Couper.

(1157)

CHIMIE GÉNÉRALE. — *Sur une nouvelle théorie chimique*; par **M. A. Couper**.
(Note présentée par *M. Dumas*.)

« J'ai l'honneur d'exposer à l'Académie les traits principaux d'une nouvelle théorie chimique que je propose pour les combinaisons organiques.

« Je remonte aux éléments eux-mêmes dont j'étudie les affinités réciproques. Cette étude suffit, selon moi, à l'explication de toutes les combinaisons chimiques, sans qu'on ait besoin de recourir à des principes inconnus et à des généralisations arbitraires.

« Je distingue deux espèces d'affinité, savoir :

« 1°. L'affinité de degré; 2° l'affinité élective.

« J'entends par affinité de degré, l'affinité qu'un élément exerce sur un autre avec lequel il se combine en plusieurs proportions définies. Je nomme affinité élective, celle que différents éléments exercent les uns sur les autres, avec des intensités différentes. Prenant pour exemple le carbone, je trouve qu'il exerce son pouvoir de combinaison en deux degrés. Ces degrés sont représentés par CO² et CO³, c'est-à-dire par l'oxyde de carbone et l'acide carbonique, en adoptant pour les équivalents du carbone et de l'oxygène les nombres 12 et 8.

« En ce qui concerne ses affinités électives, le carbone s'éloigne des autre éléments et montre, pour ainsi dire, une physionomie particulière. Les traits qui caractérisent cette affinité élective du carbone sont les suivants :

« 1°. Il se combine avec des nombres d'équivalents égaux d'hydrogène, de chlore, d'oxygène, de soufre, etc., qui peuvent se remplacer mutuellement pour satisfaire son pouvoir de combinaison.

« 2°. Il entre en combinaison avec lui-même.

« Ces deux propriétés suffisent à mon avis pour expliquer tout ce que la chimie organique offre de caractéristique. Je crois que la seconde est signalée ici pour la première fois. A mon avis, elle rend compte de ce fait important et encore inexpliqué de l'accumulation des molécules de carbone dans les combinaisons organiques. Dans les composés où 2, 3, 4, 5, 6, etc., molécules de carbone sont liées ensemble, c'est le carbone qui sert de lien au carbone.

« Ce n'est pas l'hydrogène qui peut lier ensemble les éléments des corps organiques. Si, comme le carbone, il avait le pouvoir de se combiner à lui-même, on devrait pouvoir former les composés H^2Cl^2, H^2Cl^3, H^2Cl^4.

Cet...

Kekulé's Contribution

Kekulé was born in 1829 in Darmstadt, Germany, Originally designed for a career in architecture, he was converted to chemistry by Liebig. But let us hear about his training from Kekulé himself (*15*).

In high school I showed particular aptitude in mathematics and drawing. My father, who was a close friend of a number of famous architects, decided that I should study architecture. It seemed to be the fact that parents normally decide the vocations of their sons. Accordingly, I entered the university (as *studiosus architecturae*) and followed with commendable diligence under Ritgen's guidance descriptive geometry, perspective, shadow-theory, stonecutting, and other interesting subjects. But Liebig's lectures tempted me to change subjects and this I decided to do....

My years of apprenticeship took me to Paris, where I was able to listen to what I believe were the last lectures of the famous Dumas. I spent much time with Wurtz with whom a close friendship later developed. By accident I met and became friends with Gerhardt, who at that time was discovering the acid anhydrides and was preparing the completed manuscript of his famous textbook for the printer. A stay of a year and a half at a lonely Swiss Castle [chemical assistant to Baron von Planta] gave me ample leisure to assimilate independently the insights I had gained from the still unpublished manuscript. My travel years took me farther to London. While Paris gave me the opportunity to become acquainted with the unpublished views of Gerhardt, so now I had the good fortune to become good friends with Williamson and to familiarize myself with the mode of thought of this philosophical intellect. Originally a student of Liebig, I had become a student of Dumas, Gerhardt, and Williamson. No longer did I belong to any one school.

This circumstance and the direction which my earlier architectural studies gave my intellect—an irresistable urge to visualize everything—these seem to be the reasons why the chemical ideas which were in the air twenty-five years ago found suitable soil inside my head. The human being, it seems clear, is the product of the conditions in which he grew up; no merit accrues to him for what he becomes.

Kekulé's account of how he arrived at the conception of the structural theory is famous.

During my stay in London I resided for a considerable time in Clapham Road in the neighborhood of Clapham Common. I frequently, however, spent my evenings with my friend Hugo Müller at Islington at the opposite end of the metropolis. We talked of many things, but most often of our beloved chemistry. One fine summer evening I was returning by the last bus, "outside," as usual, through the deserted streets of the city, which are at other times so full of life. I fell into a reverie (Traümerei), and lo, the atoms were gamboling before my eyes. Whenever, hitherto, these diminutive beings had appeared to me, they had always been in motion; but up to that time I had never been able to discern the nature of their motion. Now, however, I saw how, frequently, two smaller atoms united to form a pair; how a larger one embraced the two smaller ones; how still larger ones kept hold of three or even four of the smaller; whilst the whole kept whirling in a giddy dance. I saw how the larger ones formed a chain, dragging the smaller ones after them but only at the ends of the chain. I saw what our past master, Kipp, my highly honored teacher and friend, has depicted with such charm in his "Molekularwelt;" but I saw it long before him. The cry of the conductor, "Clapham Road," awakened me from my dreaming; but I spent a part of the night in putting on paper at least sketches of these dream forms. This was the origin of the "Structure Theory."

Kekulé's important paper, "On the Constitution and Metamorphoses of Chemical Compounds and on the Chemical Nature of Carbon" appeared in May, 1858, when he was but 29 years old. In this paper Kekulé clearly presents the proposal that carbon is tetravalent and is capable of uniting with itself to form chains. In his own words (*1*, *16*):

If only the simplest compounds of carbon are considered (marsh gas, methyl chloride, carbon tetrachloride, chloroform, carbonic acid, phosgene gas, carbon disulfide, prussic acid, etc.), it is striking that the amount of carbon which the chemist has known as the least possible, as the *atom*, always combines with four atoms of a monatomic or two atoms of a diatomic, element, that generally, the sum of the chemical unities of these elements which are bound to one atom of carbon is equal to 4. This leads to the view that carbon is *tetratomic* (or tetrabasic)....

For substances which contain more atoms of carbon, it must be assumed that at least part of the atoms are held just by the affinity of carbon and that the carbon atoms themselves are joined together, so that naturally a part of the affinity of one for the other will bind an equally great part of the affinity of the other

The simplest, and therefore the most obvious, case of such linking together of two carbon atoms is this, that one affinity unit of each atom is bound to one of the other....In other words, one group of two atoms of carbon = C_2 will be hexatomic, it will form compounds with six atoms of a monatomic element....

When comparisons are made between compounds which have an equal number of carbon atoms in the molecule and which can be changed into each other by simple transformations (e.g., alcohol, ethyl chloride, aldehyde, acetic acid, glycolic acid, oxalic acid, etc.) the view is reached that the carbon atoms are arranged in the same way and only the atoms held to the carbon skeleton are changed.

It is appropriate to close this review of Kekulé's contribution with a further quotation from his 1890 address:

One cannot explore new countries in express trains, nor will the study of even the best textbook qualify a man to become a discoverer. Whoever is content to follow well-laid promenades until he reaches some pleasant eminence frequented by tourists, may, by striking into thickets, gather some forgotten flower; or if cryptograms, mosses and lichens satisfy him he may even bring home a well-filled vasculum; but anything essentially new he will not find. Whoever wishes to train himself as an investigator must study the traveler's original works; and that, too, so thoroughly that he is able to read between the lines—to divine the author's unexpressed thought. He must follow the paths of the Pathfinders; he must note every footprint, every bent twig, every fallen leaf. Then, standing at the extreme point reached by his predecessors, it will be easy for him to perceive where the foot of a further pioneer may find solid ground.

Couper's Contribution

Archibald Scott Couper (*17*, *18*) was born in 1831 at Kirkintilloch, in Scotland. As a child his health was poor and he received most of his education at home. His university studies began in Glasgow and emphasized the humanities and languages. In 1852, at the age of 21, he attended the University of Edinburgh, where he studied logic, metaphysics, and moral philosophy. Certainly an unusual background for a future chemist!

Some time between the years 1854 to 1856 Couper decided to study chemistry. After relatively brief preparative work at Edinburgh, he went to Wurtz's laboratory in Paris and almost immediately began independent work. His first paper, "Recherches sur la benzine" was published in 1857 and reported the preparation of two new compounds, bromobenzene and *p*-dibromobenzene. A second paper, on salicylic acid, was presented to the French Academy of Sciences in 1858.

A few months earlier Couper had arrived at the concept of the tetravalence of carbon and the self-linking of carbon atoms. He described his ideas in a paper entitled "On a New Chemical Theory" and requested Wurtz to present it to the French Academy. Unfortunately, Wurtz failed to act, and Kekulé's paper appeared on May 19, 1858. Couper's contribu-

tion was then presented to the academy by Dumas, on June 14, 1858.

Couper was deeply affected by Wurtz's unfortunate delay which had resulted in his views being anticipated by Kekulé, albeit by less than a month. He returned to Scotland in the role of second assistant to Lyon Playfair, Professor of Chemistry. Unfortunately, he soon suffered a nervous breakdown, from which he never fully recovered. It is not possible to say whether his severe disappointment was a factor. His life for the next thirty-four years was spent at his home in Kirkintilloch, away from any significant intellectual activity.

Couper's approach is illustrated by these quotations from his paper (*2*).

> The end of chemistry *is its theory*. The guide in chemical research *is a theory*.
>
> * * *
>
> There are two conditions which every sound theory must fulfil:
>
> 1. It must be proved to be empirically true.
> 2. It must no less be philosophically true.

After discussing the Theory of Types, he concludes that the empirical truth of the theory must be admitted. He then points out, "The philosophical test demands that a theory be competent to explain the greatest number of facts in the simplest possible manner." He then proceeds to point out that the Theory of Types makes no attempt to explain the facts.

Just as Kekulé used his earlier architectural training in his approach, Couper utilized his earlier linguistic training in criticizing the Theory of Types.

> Should the principle which is therein adopted be applied to the common events of life, it will be found that it is simply absurd. Suppose that some one were to systematize the formation of letters into words that formed the contents of a book. Were he to begin by saying that he had discovered a certain word which would serve as a type, and from which by substitution and double decomposition all others are to be derived,—that he by this means not only could form new words, but new books, and books almost ad infinitum,—that this word also formed an admirable point of comparison with all others,—that in this there were only a few difficulties, but that these might be ingeniously overcome,—he would certainly state an empirical truth. At the same time, however, his method would, judged by the light of common sense, be an absurdity....
>
> The sure and invincible method of arriving at every truth which the mind is capable of discovering is always the one and the same. It is that, namely, of throwing away all generalization, of going back to first principles, and of letting the mind be guided by these alone. It is the same in common matters. It is the same in science. To reach the structure of words we must go back, seek out the undecomposable elements, viz. the letters, and carefully study their powers and bearing. Having ascertained these, the composition and structure of every possible word is revealed.

Applying his method to the analysis of carbon compounds, he arrived at the conclusion that carbon exhibits a combining power of 4 and it is capable of uniting with itself utilizing units of the combining power of the atoms involved.

In several respects his publication goes beyond that of Kekulé. The latter considered that carbon must have an invariant valence of 4; Couper is willing to assign carbon valences of both 2 (in carbon monoxide) and 4 (in carbon dioxide and methane). In his paper Kekulé nowhere attempted to write structural formulas for the compounds discussed. Couper clearly represents such molecules as methyl and ethyl alcohol, ethyl ether, propionic acid, and ethylene glycol by means of structural formulas, showing bonds between atoms linked to each other. Finally, he attempts a structural formula for salicylic acid. Although the molecule is shown as an open-chain derivative, he does show the phenolic hydroxyl and the carboxyl groups on neighboring carbon atoms, and the reaction product with phosphorus pentachloride as a ring compound in which the phosphorus atom has displaced the two acidic hydrogen atoms. Carbon atoms are linked by both single and double bonds—only a shift of a hydrogen atom and formation of a ring is required to transform it into a structure which would be acceptable today.

All in all, this is a remarkable contribution from a young man, 27 years of age, whose studies in chemistry had begun but 2 to 3 years previously.

Kekulé died in 1896. He had a long and fruitful research career. His important contributions were widely recognized and he was repeatedly honored in the course of his life.

On the other hand, Couper's chemical life was exceedingly brief. His contribution, important as it was, was soon forgotten. We are indebted to Kekulé's successor at Bonn, R. Anschütz for uncovering and pointing out to the chemical world Couper's major contribution (*19*).

We may also contrast the different approaches of the two workers. Kekulé was very well versed in the chemical theory of the day. He had studied chemistry intensively for a number of years. He was so accustomed to the Theory of Types that he found it difficult to avoid presentation of his researches in terms and symbols customary to that theory even after the publication of his revolutionary paper.

On the other hand, Couper was a relative novice in chemistry. He had little prejudice to overcome in developing his theory. Which is to be more admired—the man who proved capable of surmounting previous training and prejudice, or the novice who attained such a remarkable insight into chemical structure with so little prior training?

One Hundred Years of Structural Theory

The publications of Kekulé and Couper merely provided the first opening for modern theory, a mere crack in the dike confining organic theory for half a century. However, that crack was all that was needed. Organic research could now be directed in effort, rather than blinded. The crack was made into a fault, the rivulet into a stream, and then into a mighty river, the full flood of organic accomplishments providing a relatively smooth, rapid transit toward his objectives for the organic investigator of today.

In 1865 Kekulé proposed his structure for benzene and related aromatic compounds (*20*), and by 1874 his student Körner had demonstrated the power of isomer number in fixing the structures of benzene isomers (*21*). In 1874 van't Hoff (*22*) and Le Bel (*23*) extended the two dimensional representations of Kekulé into three dimensions, providing a simple explanation of optical isomerism. At the same time van't Hoff also used the tetrahedral carbon atom to account for *cis-trans* geometric isomers.

It was a basic tenet of the structural theory that there existed at most but one structure for each and every substance. However, cases soon were recognized where a given substance apparently required two structural formulas to describe its behavior. However the phenomenon of tautomerism was soon understood and brought within the structural theory.

Molecular rearrangements sometimes provided major difficulties in the determination of structures. Indeed more than 30 structures were proposed for camphor and its degradation product, camphoric acid, before their constitutions were satisfactorily interpreted.

The study of small ring compounds led to recognition of the strains resulting from the presence of distorted angles (*24*). In 1889 Kehrmann noted that certain substituted quinones exhibited markedly decreased reactivity and led him to postulate a steric effect resulting from the steric requirements of the substituents (*25*). The concept was developed further by Victor Meyer in his studies of the rates of esterification of ortho substituted benzoic acids (*26*). The idea revealed its importance to the structural theory in accounting for the isomerism observed in ortho substituted biphenyls (*27*).

In Conclusion

The path of the organic theorist is not an easy one. The man who synthesizes a new class of compounds receives ready recognition and acclaim. One who discovers a new reaction is applauded and will doubtless soon have his contribution recognized by having his name attached to the reaction in question, to the confusion of future generations of students.

However, consider the lot of the theorist. Should he propose a new interpretation or a new theory, his proposed interpretation or theory is immediately attacked. The referees of his paper are almost certain to point out that alternative interpretations are possible, so that the paper should not be published. Or they may state that the germ of the idea has already been suggested by someone in an obscure reference. Or they may fall back on the position that the proposed interpretation fails to account for all the published data and the author should do additional experimental work (preferably forever) before he publishes his proposal.

Should he be successful in overcoming these objectives, he faces new difficulties. Immediately upon publication other workers point out that the ideas are obvious, that these ideas had occurred to them long ago but had not been considered worthy of publication. Various workers carry out inaccurate experiments and immediately rush into print with their data to refute the new theory.

We teach our students that theories come, and theories go, but practical results stand forever.

Yes, theoretical developments are treated quite differently than are practical developments. It is not surprising that many chemists begin their work with a theoretical inclination but end their days primarily interested in the practical aspects of chemical research.

To all discouraged theoretical chemists, the achievement of Kekulé and Couper provides a beacon of encouragement. One hundred years have passed—yet their contribution shines even brighter. Both the practical worker and the organic theorist are deeply indebted to them for their magnificent contribution 100 years ago.

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Division of Chemical Education—1959

The 1959 Directory of the Division of Chemical Education went to print on January 31. The Directory lists 2044 members and 72 associates, and in addition contains useful information about the Division activities. Readers of this Journal may obtain a Directory by joining the Division. Send name, address, and dues ($1.50 for ACS members, and $2 for non-ACS members) to Elbert C. Weaver, Treasurer, Phillips Academy, Andover, Mass.

Glen A. Russell
Iowa State College
Ames

Fundamental Processes of Autoxidation

Few reactions are of greater importance or have received more attention than autoxidation, the reaction of molecular oxygen with organic materials. It is the purpose of this review to summarize the mechanism of this reaction. Since reactions of oxygen with hydrocarbons in the vapor phase at relatively high temperatures have been discussed recently by De La Mare and Vaughan (*1*), this review will be limited to liquid phase oxidations occurring at lower temperatures. Moreover, oxidations of organic materials that do not involve reaction at a carbon atom, such as the oxidation of a nitroso- to a nitro-compound, are not discussed.

It is well recognized that most autoxidations, with the exception of the oxidation of certain organometallic compounds and of some photochemical oxidations, involve the free radical chain process described by the following series of reactions (*2*).

Chain initiation

$$\text{Catalyst} \rightarrow \text{R}\cdot$$

$$\text{RH} + \text{O}_2 \rightarrow \text{R}\cdot + \text{HOO}\cdot$$

$$\text{C=C} + \text{O}_2 \rightarrow \cdot\text{CCOO}\cdot$$

$$\text{R}:^- + \text{O}_2 \rightarrow \text{R}\cdot + \cdot\text{OO}:^-$$

Chain propagation

(1) $\text{R}\cdot + \text{O}_2 \rightarrow \text{ROO}\cdot$

(2) $\text{R}\cdot + \text{O}_2 \rightarrow \text{unsaturation} + \text{HOO}\cdot$

(3) $\text{ROO}\cdot + \text{RH} \rightarrow \text{ROOH} + \text{R}\cdot$

(4) $\text{ROO}\cdot + \text{R}:^- \rightarrow \text{ROO}:^- + \text{R}\cdot$

(5) $\text{ROO}\cdot + \text{C=C} \rightarrow \text{ROOCC}\cdot$

(6) $\text{ROO}\cdot + \text{C=C} \rightarrow \text{RO}\cdot + \text{C}\overset{\text{O}}{\text{—}}\text{C}$

(7) $\text{ROO}\cdot + \text{ROO}\cdot \rightarrow 2\text{RO}\cdot + \text{O}_2$

Chain termination

$$\left.\begin{matrix}\text{R}\cdot + \text{ROO}\cdot \rightarrow \\ 2\text{ROO}\cdot \rightarrow\end{matrix}\right\} \text{nonradical products}$$

Free radical intermediates are formed in the initiation process and destroyed in the termination reaction. The products of the reaction are determined by the nature of the propagation steps. Alkyl radicals can react with oxygen either to form a peroxy radical (reaction 1) or, more rarely, to lose a hydrogen atom and yield a dehydrogenated product (reaction 2). Depending on the nature of the material being oxidized a peroxy radical can give rise to a hydroperoxide or a peracid (reaction 3), the anion of a hydroperoxide (reaction 4), a polymeric peroxide (reaction 5), an epoxide (reaction 6) or the reaction products from an alkoxy radical (reactions 6 and 7). Among the most common reaction products of alkoxy radicals are alcohols and carbonyl compounds.

Presented at the Gordon Research Conference on Petroleum, Colby Junior College, June, 1958.

Initiation Processes

Autoxidations are readily catalyzed by substances which yield free radicals upon decomposition. Typical catalysts are aliphatic azo compounds, peroxides, and hydroperoxides. Since hydroperoxides can be both catalysts and reaction products, many autoxidations have an autocatalytic nature.

The initiation of oxidation by a direct reaction between oxygen and the organic substance has been observed experimentally only occasionally. The reaction of ethyl linoleate with oxygen has been studied very thoroughly in this regard (*3*). Originally, it was believed that a thermal reaction had been observed since the rate of oxidation was observed to be proportional to the amount of oxygen absorbed as shown by the solid line in Figure 1 (*3a*). Such a relationship is consistent with the occurrence of a chain process involving the following steps:

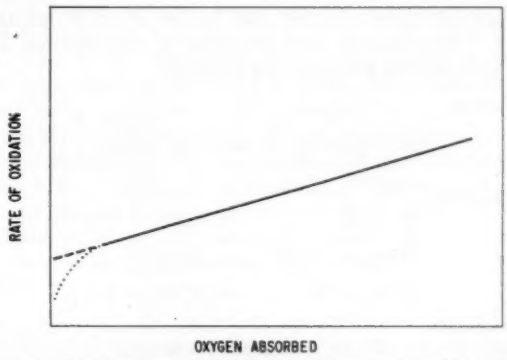


Figure 1. Relationship between the amount of oxygen absorbed and the rate of oxidation of ethyl linoleate (after Bolland and Bateman).

Initiation

$$2\text{ROOH} \rightarrow \text{RO}\cdot + \text{ROO}\cdot + \text{H}_2\text{O}$$

Propagation

$$\text{R}\cdot + \text{O}_2 \rightarrow \text{ROO}\cdot$$

$$\text{ROO}\cdot + \text{RH} \rightarrow \text{ROOH} + \text{R}\cdot$$

Termination

$$2\text{ROO}\cdot \rightarrow \text{nonradical products}$$

The bimolecular nature of the initiation by hydroperoxide was independently verified (*4*). Extrapolation of the straight line in Figure 1 gives a definite intercept which was originally interpreted as being due to a thermal reaction between oxygen and the olefin. However, experiments at extremely low hydroperoxide concentrations indicated that the rate of oxidations actually followed the dotted line of Figure 1 (*3b*). This behavior is consistent with an initiation process that is bimolecular in hydroperoxide at high hydroperoxide con-

centrations but unimolecular at low concentrations. Because of the curvature of the dotted line in Figure 1 it is impossible to state whether a direct thermal reaction between ethyl linoleate and oxygen can be detected.

A thermal initiation reaction between indene and oxygen has been observed (*5*). Figure 2 demonstrates

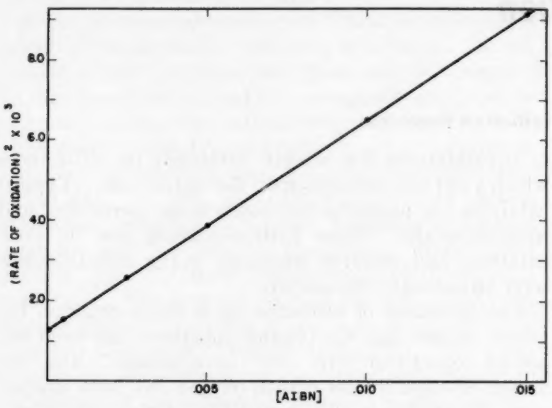


Figure 2. Oxidation of indene at 50°, 760 mm oxygen pressure; concentrations and rates in moles, liters, and hours.

the dependence of rate upon α,α'-azodiisobutyronitrile concentrations for the catalyzed oxidation of indene. The rate of oxidation at zero catalyst concentration is dependent upon oxygen and hydrocarbon concentration. The kinetics and products of the reaction are consistent with the following process:

Initiation

$$RH + O_2 \rightarrow R\cdot + HOO\cdot \text{ (or } \cdot CCOO\cdot)$$

Propagation

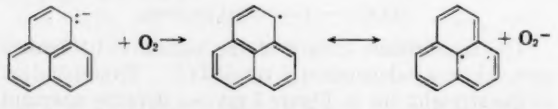
$$R\cdot + O_2 \rightarrow ROO\cdot$$
$$ROO\cdot + C{=}C \rightarrow ROOCC\cdot$$
$$ROO\cdot + RH \rightarrow ROOH + R\cdot$$

Termination

$$2ROO\cdot \rightarrow \text{nonradical products}$$

The kinetics of the oxidation of indene are inconsistent with a thermal reaction involving hydroperoxide formation by a nonradical process.

Certain carbanions (the negative ion formed by the addition of an electron to a radical) react readily with oxygen with the formation of an alkyl radical. Although this is not a common initiation reaction, an example of this type of reaction is furnished by the reaction of oxygen with the perinaphthyl anion to yield the perinaphthyl radical (*6*).



Salts of cobalt and manganese are often used as oxidation catalysts, particularly in the drying of paints and oils. There is some evidence in support of an initiation reaction involving hydrocarbon, cobaltII ion, and oxygen (*7*). However, evidence that this reaction, if it occurs, must be very slow has been presented by Blanchard (*8*). In Figure 3 the rates of

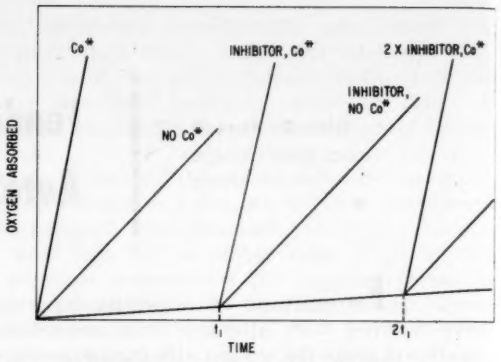


Figure 3. Oxidation of cumene in acetic acid (after Blanchard).

oxidation of cumene at 50° in the presence and absence of cobaltII acetate and the oxidation inhibitor 2,6-di-*t*-butyl-*p*-cresol (but always in the presence of the initiator α,α'-azodiisobutyronitrile) are given. In the absence of cobaltII ion the final rate of oxidation of cumene is independent of the presence of the inhibitor except that a definite period of inhibition (t_1) is observed. If the concentration of inhibitor is doubled this inhibition period is also doubled. In the presence of cobaltII acetate a faster rate of oxidation is observed but there is no effect on the inhibition periods. These results indicate that the direct reaction between cumene, cobaltII ion, and oxygen to produce free radicals must be very slow since otherwise the inhibition period would have been shortened by the addition of cobaltII ion. The major initiation reaction of cobaltII ion thus appears to be one of inducing the decomposition of hydroperoxide (*9*).

$$Co^{+2} + ROOH \rightarrow Co^{+3} + OH^- + RO\cdot$$
$$Co^{+3} + ROOH \rightarrow Co^{+2} + ROO\cdot + H^+$$

Chain Propagation

Reactions of Alkyl Radicals

As mentioned earlier, the propagation reactions are the product-controlling reactions of the autoxidation sequence. Once an alkyl radical has been generated in an initiation reaction it nearly always reacts readily with oxygen. Oxygen itself is a diradical, and the reaction of an alkyl radical with oxygen is essentially a radical coupling reaction.

$$R\cdot + \cdot\ddot{O}{-}\ddot{O}\cdot \rightarrow ROO\cdot$$

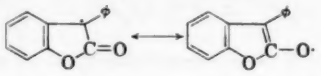
The ease with which this reaction occurs can be judged from the observation that, toward a polysytrenyl radical, oxygen is about 1×10^6 times as reactive as styrene even though styrene is extremely reactive toward free radicals (*10*).[2]

$$\sim\!CH\phi\cdot + CH_2{=}CH\phi \xrightarrow{k_p} \sim\!CH\phi CH_2CH\phi\cdot$$
$$\sim\!CH\phi\cdot + O_2 \xrightarrow{k_0} \sim\!CH\phi OO\cdot$$
$$k_0/k_p \cong 1 \times 10^6$$

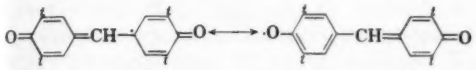
The rate constants for the reaction of oxygen with most alkyl radicals are approximately of the same magnitude as the rate constants for the interaction of

[2] In this and subsequent formulas, the symbol ϕ stands for the phenyl group, and *t* stands for the tertiary butyl group.

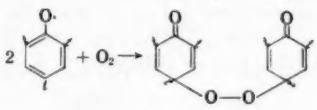
two alkyl radicals. . However, some radicals, usually those with outstanding resonance stability, are stable to oxygen. For example radicals such as



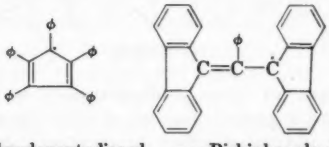
or



are inert to oxygen (*11*, *12*). In these cases resonance structures involving the presence of the odd electron on oxygen may be considerably more stable than other resonance forms and the radicals may more properly be considered to be an alkoxy or phenoxy radical. However, even some phenoxy radicals, for example 2,4,6-tri-*t*-butylphenoxy, react readily with oxygen (*13*).



Other radicals, not involving a resonating system containing any atom other than carbon, are known to be stable or to react only slowly with oxygen. The perinaphthyl (*6*), pentaphenylcyclopentadienyl (*14*) and α,γ-bisbiphenylenephenylpropenyl (*15*) radicals are examples of radicals possessing outstanding stability toward oxygen. All of these materials possess



Pentaphenylcyclopentadienyl radical

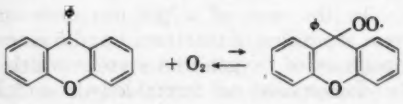
α,γ-Bisbiphenylene-β-phenylallyl radical

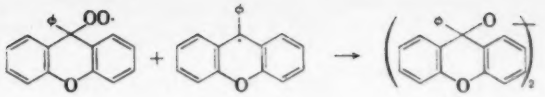
unique resonance stabilization.

Some radicals of intermediate stability must be able to enter into an equilibrium with oxygen

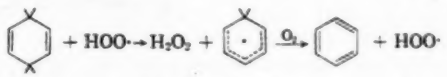
$$R\cdot + O_2 \rightleftharpoons ROO\cdot$$

Although this equilibrium has never been experimentally verified, it seems appropriate to suggest that it is often important whenever radicals can react with oxygen in the presence of the parent hydrocarbon to give the dialkyl peroxide in preference to the hydroperoxide. For example, radicals that react readily with oxygen such as the diphenylmethyl radical, yield the hydroperoxide when generated in the presence of oxygen and the parent hydrocarbon. More stable radicals, such as the 9-phenylxanthyl, yield the dialkyl peroxide (*16*). Here equilibriums between the radical, oxygen, and peroxy radical may give only a low concentration of the peroxy radical in the presence of the alkyl radical—a condition favorable for the formation of the dialkyl peroxide and not the hydroperoxide.





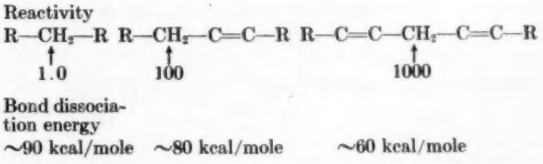
In a few cases alkyl radicals react with oxygen by loss of a hydrogen atom. For example, autoxidation of 1,4-cyclohexadiene is reported to yield benzene (*17*). Here, the driving force for the formation of aromaticity apparently accounts for the occurrence of reaction 2 instead of reaction 1.



Reactions of Peroxy Radicals

Depending upon the structure of the material being oxidized, peroxy radicals can react in a number of ways (reaction 3–7). The most common reaction is the abstraction of a hydrogen atom to give a molecule of hydroperoxide and to regenerate an alkyl radical. This reaction is commonly observed for hydrogen atoms alpha to an unactivated double bond, aromatic ring, ether linkage or for aldehydic hydrogen atoms. Hydrogen atoms attached to 3°- or 2°-carbon atoms in aliphatic or alicyclic systems are attacked somewhat less readily while unactivated 1°-hydrogen atoms are seldom attacked except at elevated temperatures.

The major factors controlling the reactivity of a carbon-hydrogen bond toward a peroxy radical are the resonance stabilization of the alkyl radical being formed and the availability of electrons at the carbon-hydrogen bond being ruptured. The importance of resonance stabilization is indicated by the relative reactivities of methyl stearate, oleate, and linoleate toward a peroxy radical (*2*). Activation of a secondary hydrogen atom by one double bond increases reactivity nearly 100-fold and a further rate increase of 10-fold occurs when the methylene group is situated between two double bonds.



Similarly, the relative reactivities of the α-hydrogen atoms of toluene, ethylbenzene, and cumene toward a peroxy radical are 0.08, 0.5, 1.00 (*18*). This reactivity sequence again is in agreement with the strengths of the 1°-, 2°- and 3°-carbon-hydrogen bonds involved. Numerous other examples demonstrating the correlation between reactivity and resonance stabilization of the incipient alkyl radical could be cited (*18*, *19*).

The reactivities of various ring-substituted cumenes (*18*) and benzaldehydes (20) toward a peroxy radical have demonstrated a polar effect in the reactions of peroxy radicals. Electron-supplying substituents increase reactivity while electron-withdrawing substituents decrease reactivity. In fact, there is a quantitative relationship between reactivity and the electrical effect of the substituent. In Figure 4 the log of the relative reactivities of cumene (k_0) and substituted cumenes (k_x) have been plotted as a function of the

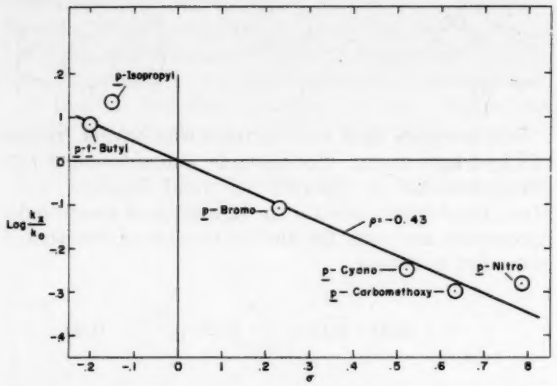
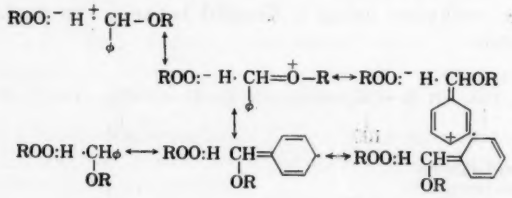


Figure 4. Correlation between reactivity of cumene (k_0) and substituted cumenes (k_x) toward peroxy radicals and σ.

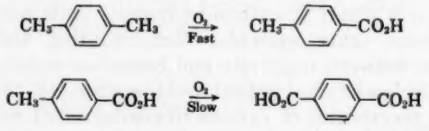
Hammett σ-constant. An excellent linear relationship results. This has been interpreted in terms of resonance in the transition state for the reaction between a peroxy radical and a carbon-hydrogen bond.

$$ROO\cdot + R'H \rightarrow [\underset{(I)}{ROO:^- H^+ \cdot R'} \longleftrightarrow \underset{(II)}{ROO:H \cdot R'}] \rightarrow ROOH + R\cdot'$$

Resonance structure (I) will be stabilized by electron-supplying substituents and destabilized by electron-withdrawing substituents in R′. Resonance structure (II) explains the effects of the stability of the incipient radical upon the reactivity of a carbon-hydrogen bond. When both polar and radical stability effects compliment each other the reactivity of a carbon-hydrogen bond toward a peroxy radical can be very high. Thus ethers are very reactive toward peroxy radicals because both resonance structures (I) and (II) are very stable.

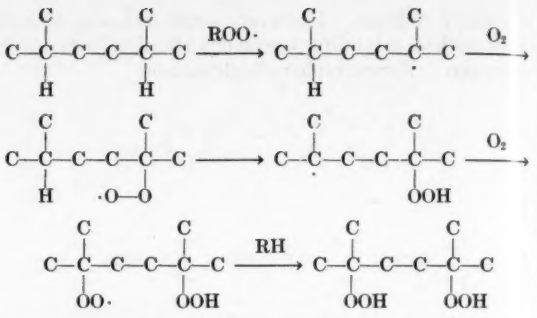


One practical consequence of the polar effect is that *p*-xylene is much more reactive than *p*-toluic acid toward a peroxy radical.

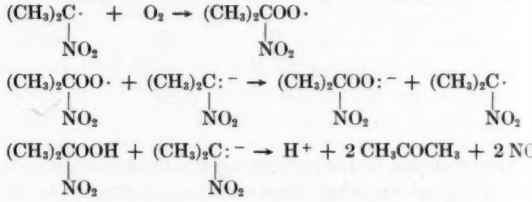


Attack of a peroxy radical upon a carbon-hydrogen bond can occur by an intermolecular or intramolecular reaction. An intramolecular reaction is especially favored in aliphatic systems if two reactive hydrogen atoms are located in 1,4 positions (*21*).

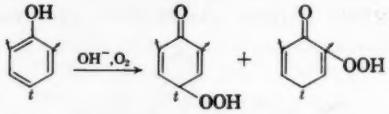
Another process by which a peroxy radical can give rise to a molecule of hydroperoxide involves electron transfer with an anion (reaction 4). This process has



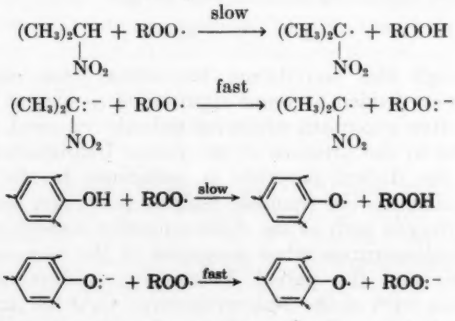
been demonstrated to occur in the oxidation of 2-nitropropane in aqueous basic solution (*22*) as well as in the oxidation of other anions. In the oxidation of 2-nitropropane the resulting hydroperoxide is not stable but gives a quantitative yield of acetone and nitrite ion upon reaction with another 2-nitropropane anion.



In other cases, for example the oxidation of 2,4,6-tri-*t*-butylphenol, the hydroperoxide is not decomposed by the anion and may be isolated (*23*).



In the absence of bases 2-nitropropane is very unreactive toward a peroxy radical, mainly because of the unfavorable inductive effect of then itro group, while 2,4,6-tri-*t*-butylphenol is recognized as an oxidation inhibitor. In both cases the anions can undergo a reaction that must be extremely slow for the unionized molecule.



Addition of Peroxy Radicals to Double Bonds

Although peroxy radicals react with unactivated double bonds containing α-hydrogen atoms by hydrogen abstraction, activated double bonds of polymerizable olefins, diolefins, and ketenes prefer to react by addition. In the case of a polymerizable molecule like styrene, repetition of reactions 1 and 5 gives rise to a 1:1 copolymer of oxygen and styrene which can be thermally decomposed to formaldehyde and benzal-

dehyde or reduced to phenylethylene glycol (*10*).

$$\phi CH{=}CH_2 + O_2 \longrightarrow -(\phi CHCH_2OO)-_n$$

$$\phi CHO + CH_2O \xleftarrow{\Delta} \xrightarrow{LiAlH_4} \phi CHOHCH_2OH$$

Formation of polymeric peroxides occurs for certain olefins which are otherwise inert to free radical polymerizations, such as β-methylstyrene (*24*) or 1,1-diphenylethylene (*25*). The ease of addition of a peroxy radical to a double bond is again determined mainly by the stability of the radical formed. Thus a peroxy radical always adds to styrene to yield a β-substituted α-phenethyl radical,

$$ROO\cdot + \phi CH{=}CH_2 \longrightarrow ROOCH_2\dot{C}H\phi$$

Moreover, α-methylstyrene which can yield a more stable β-substituted α-methyl-α-phenethyl radical is 2-3 times as reactive toward a peroxy radical as styrene (*24*). Similarly, methacrylonitrile is more reactive than acrylonitrile and isopropenylmethyl ketone more reactive than vinylmethyl ketone (*26*).

Relative Reactivity Toward Peroxy Radicals

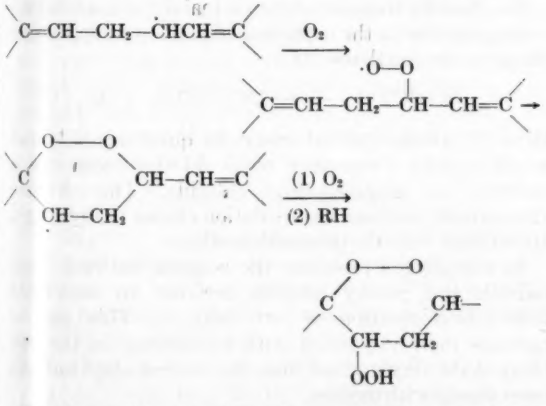
$$\phi\overset{CH_3}{\overset{|}{C}}{=}CH_2 > \phi CH{=}CH_2$$

$$CN\overset{CH_3}{\overset{|}{C}}{=}CH_2 > CNCH{=}CH_2$$

$$CH_3\overset{CH_3}{\overset{|}{C}}{=}CH_2 > CH_3\overset{O}{\overset{\|}{C}}CH{=}CH_2$$

Presumably, polar effects are important in the addition of a peroxy radical to a double bond but their importance has never been demonstrated. It is expected, as in the case of hydrogen abstraction, that electron-supplying groups will increase the reactivity of the double bond and electron-withdrawing groups will decrease their reactivity.

Addition of a peroxy radical to a double bond can also be either an intermolecular or intramolecular reaction. Intramolecular reaction is often observed in the oxidation of 1,5-diolefins, such as squalene (*27*).



The formation of polymeric peroxides by reaction 5 followed by 1 is sometimes complicated by the occurrence of reaction 6. The formation of epoxides as primary oxidation products usually, but not necessarily always, involves reaction 5 followed by 6*a*, 6*a* occurring in competition with 1 (*28*). Reaction 6 may also occur

$$ROO\cdot + RCH{=}CH_2 \rightarrow ROOCH_2\dot{C}HR \quad (5)$$

$$ROOCH_2\dot{C}HR + O_2 \rightarrow ROOCH_2CHROO\cdot \quad (1)$$

$$ROOCH_2\dot{C}HR \rightarrow RO\cdot + \underset{O}{\overset{\diagup\diagdown}{CH_2{-}CHR}} \quad (6a)$$

directly without the formation of an intermediate β-peroxy alkyl radical. The relative rates of 6*a* and 1 determine whether the polymeric peroxide or the epoxide will be the major reaction product. The importance of 6*a* increases with the stability of the $ROOCH_2\dot{C}HR$ radical(III) because, the slower III reacts with oxygen the more chance it will have to decompose unimolecularly. Thus, under the same reaction conditions the oxidation of α-methylstyrene gives a higher yield of epoxide than does styrene. As would be expected, the per cent of oxygen reacting that enters into epoxide increases rapidly as the oxygen pressure is lowered. Figure 5 demonstrates this behavior for the oxidation of α-methylstyrene (*29*). Again this behavior is consistent with the competition

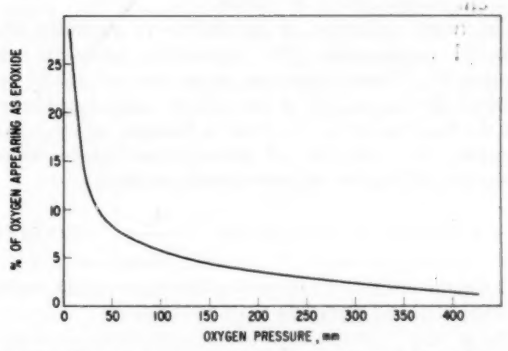
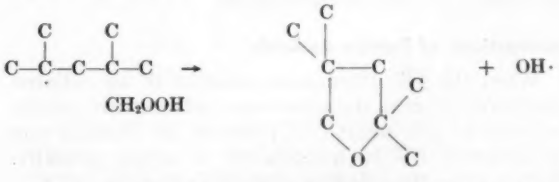


Figure 5. Effect of oxygen pressure on the products of the oxidation of α-methylstyrene at 50° (after Miller and Mayo).

between 1 and 6*a*, the lifetime of III being considerably increased by lowering the oxygen pressure and the probability of the occurrence of 6*a* thereby increased. Reaction 6*a* and analogous reactions are also favored by higher temperatures. Thus at elevated temperatures 1,3- and 1,4-oxides can be formed from peroxy radicals, presumably by the following intramolecular reaction (*30*).



When reaction 6*a* occurs an alkoxy radical is also produced. Alkoxy radicals can regenerate a new alkyl radical and continue the oxidation chain by hydrogen abstraction, (reaction 6*b*) addition to a double bond (reaction 6*c*) or by decomposition with carbonyl formation (reaction 6*d*).

$$RO\cdot + RH \rightarrow ROH + R\cdot \quad (6b)$$

$$RO\cdot + RCH{=}CH_2 \rightarrow ROCH_2\dot{C}HR \quad (6c)$$

$$RO\cdot \rightarrow {>}C{=}O + R'\cdot \quad (6d)$$

Thus the formation of epoxides in the oxidation of an unsaturated material is accompanied by either alcohol, ether or carbonyl formation. When the alkoxy radical

has a polymeric oxygen-olefin composition, as occurs in the oxidation of α-methylstyrene, its decomposition can involve the formation of a number of molecules of carbonyl compounds.

$$\mathrm{ROOCH_2CH\phi OOCH_2CH\phi O\cdot} \rightarrow \mathrm{RO\cdot + CH_2O + \phi CHO + CH_2O + \phi CHO} \quad (6d')$$

The effect of oxygen pressure on the products of the oxidation of α-methylstyrene (*29*) thus demonstrates an interesting interplay between reactions 1, 5, 6*a*′ and 6*c*. At high oxygen pressure 1 overshadows 6*a* and a polymeric peroxide results. As the oxygen pressure is reduced reaction 6*a* and the chain decomposition reaction 6*d*′ become more important and the epoxide, formaldehyde and acetophenone become the major primary oxidation products. At very low oxygen pressures reaction 6*a* nearly always occurs before reaction 1 and therefore the polymeric radical cannot be synthesized. Reaction 6*c* is now very important and a major reaction product is a polymeric ether arising from reactions 6*c*, 1, 5, and 6*a*.

The ready oxidation of haloölefins to epoxides and carbonyl compounds (*31*) apparently proceeds via reaction 6. These oxidations often proceed easily because of the instability of the alkoxy radical produced and its decomposition to yield a halogen atom. For example, the oxidation of tetrachloroethylene seems best explained by the following chain reaction

$$\mathrm{Cl\cdot + Cl_2C{=}CCl_2 \longrightarrow Cl_3CCCl_2\cdot \xrightarrow{O_2} Cl_3CCl_2OO\cdot}$$

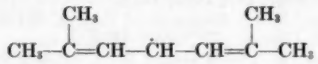
$$\mathrm{Cl_3CCCl_2OO\cdot + Cl_2C{=}CCl_2 \longrightarrow Cl_3CCl_2O\cdot + Cl_2C\text{—}O\text{—}CCl_2}$$

$$\mathrm{Cl_3CCl_2O\cdot \longrightarrow Cl_3CCOCl + Cl\cdot}$$

The interesting reaction between oxygen, phosphorous trichloride and an alkane to yield either $RPOCl_2$ or $ROPCl_2$ and phosphorous oxychloride apparently involves a somewhat similar reaction (*32*).

$$\mathrm{Cl\cdot + RH \rightarrow HCl + R\cdot}$$
$$\mathrm{R\cdot + O_2 \rightarrow ROO\cdot}$$
$$\mathrm{ROO\cdot + PCl_3 \rightarrow (ROOPCl_3\cdot) \rightarrow RO\cdot + POCl_3}$$
$$\mathrm{RO\cdot + PCl_3 \rightarrow ROPCl_3\cdot \rightarrow RPCl_3 \rightarrow RPOCl_2 + Cl\cdot}$$
$$\mathrm{\quad\quad\quad

librium partial pressure of 10 mm) at 45° when RH is ethyl linoleate but for a more stable radical such as the dimethylheptadienyl radical shown below,



reaction 9 predominates below 1000 mm or oxygen pressure at 25° (*36*).

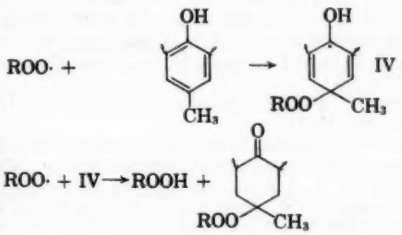
The addition of triphenylmethane to an oxidation of cumene will drastically reduce the over-all rate of oxidation by a reduction in the total peroxy concentration (*18*). A possible explanation is that triphenylmethane is much more reactive than cumene toward peroxy radicals while the triphenylmethyl radical either reacts only slowly with oxygen or possibly enters into an equilibrium with oxygen. These conditions are very favorable for chain termination by reaction 9 and unfavorable for chain propagation.

$$ROO\cdot + \phi_3CH \longrightarrow ROOH + \phi_2C\cdot$$

$$\phi_3C\cdot + O_2 \rightleftharpoons \phi_3COO\cdot$$

$$\phi_3C\cdot + ROO\cdot \longrightarrow \phi_3COOR$$

This type of termination is the reaction involved in the function of most oxidation inhibitors. For example, a phenolic-type inhibitor inhibits autoxidation by trapping a peroxy radical to yield a new radical that cannot react with oxygen readily. This new radical, whose formation represents the ending of one kinetic chain, can end still another kinetic chain by reacting with another peroxy radical to yield a cyclohexadienone.

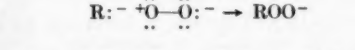


Oxidation of Organometallics

Although a free radical chain mechanism occurs in the autoxidation of many resonance stabilized anions, more reactive organometallic materials apparently can react with oxygen without the intervention of free radical intermediates. Peroxidic materials are apparently the initial products of these reactions. For example, Grignard reagents react with oxygen to yield hydroperoxide salts (*37a*).

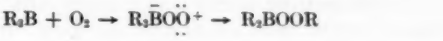
$$RMgX + O_2 \rightarrow ROOMgX$$

The fluorenyl carbanion also is reported to react directly with oxygen to form the hydroperoxide (*37b*). This reaction can be considered to involve the reaction of an incipient carbanion from the Grignard reagent with an activated form of oxygen.



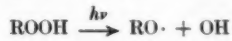
This reaction does not generally occur for carbanions because the dipolar form of oxygen has an energy content 38 kcal/mole above that of ordinary oxygen (*38*). This activation energy can be supplied only by the most reactive organometallic compounds.

The reaction of trimethylboron with oxygen apparently proceeds in a manner similar to the oxidation of Grignard reagents. Here the product of the reaction is a peroxide possibly formed by an ionic re-arrangement (*39*).

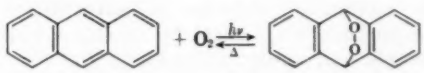


Photochemical Oxidations

Two distinct oxidation processes can occur in the presence of light. One involves the initiation of a free radical chain process similar to that described previously (reactions 1–8). In this case quantum efficiency of the reaction will be much greater than 1 and the reaction will be autocatalytic due to the initiation process

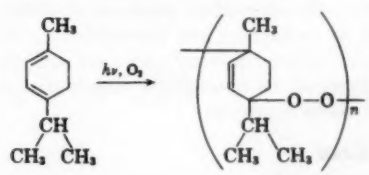


A second photochemical process apparently involves the activation of an unsaturated system to a diradical which subsequently reacts with oxygen to form a cyclic peroxide. This process will have a quantum efficiency not exceeding 1. A well-recognized example of this type of reaction is the formation of photoperoxides from numerous polynuclear aromatic hydrocarbons (*40*).

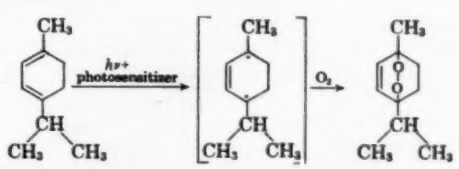


A remarkable feature of these photoperoxides is their ability to give back oxygen, often in a quantitative manner, upon heating. Rubrene which forms a photoperoxide rapidly in ultraviolet light gives no detectable reaction with oxygen in the absence of light over a $7^1/_2$ year reaction period.

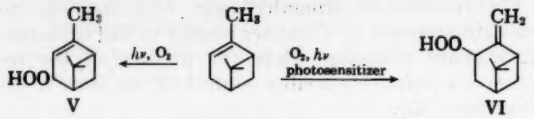
A modification of this reaction involves "photosensitization" (*41*). Photosensitizers apparently absorb energy and then activate unsaturated systems to the diradical stage. For example, the photochemical oxidation of α-terpinene yields the polymeric peroxide expected from a free radical chain reaction (*41*).



However, in the presence of any of a number of organic materials capable of fluorescence, such as methylene blue, chlorophyll or rubrene, the reaction product in dilute solution is ascaridole, a transannular peroxide (*42*).

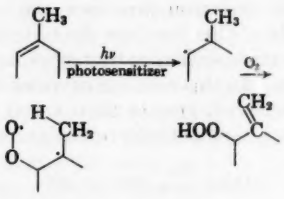


Similarly, the photo-initiated oxidation of α-pinene yields (V) (by a chain process) whereas photosensitized oxidation yields (VI) (*43*).



V VI

Photosensitized reaction of oxygen with an unactivated double bond apparently involves diradical formation followed by intramolecular hydrogen abstraction.



Formation of a hydroperoxide in this manner will always involve allylic rearrangement and will be favored by dilution.

Degradative Oxidations

The previous sections have described processes by which hydroperoxides, polymeric peroxides, epoxides, alcohols, and carbonyl compounds can be formed as primary oxidation products of autoxidation. All of these products are formed by reactions which are quite simple and easily understood; the only complexity of the reaction scheme results from the number of possible reactions rather than from the complexity of any single step of the reaction. When oxidations are performed under conditions where the initially formed products, particularly peroxidic materials, are unstable the reaction sequence is complicated by still further reactions. For example, by use of elevated temperatures, heavy metal ions, strongly basic or acidic media and high degrees of oxidations the conversion of a methylene group to a carbonyl group or a methyl group to a carboxyl group can be achieved by a combination of radical and ionic reactions. Under conditions where the initially formed peroxides or hydroperoxides decompose readily, products are often formed as a result of radical-radical interactions. Moreover, since alkoxy radicals, acyloxy and acyl radicals are unstable, rupture of carbon-carbon bonds frequently occurs under these conditions.

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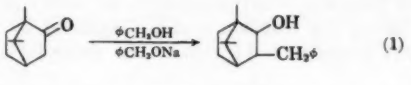

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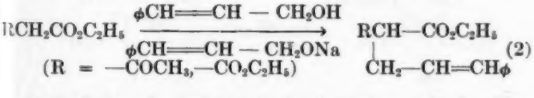

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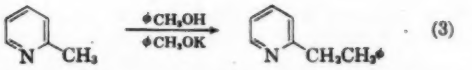

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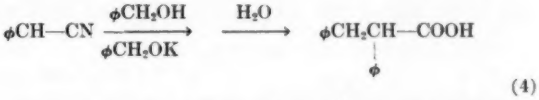

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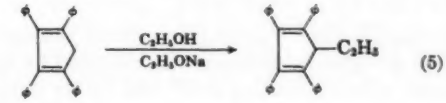

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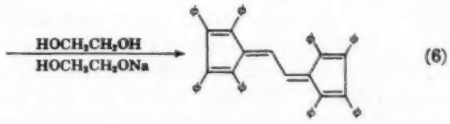

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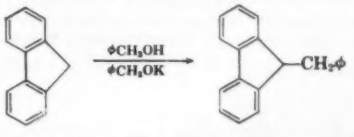

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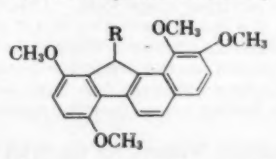
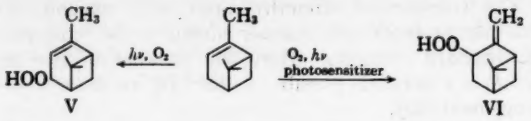


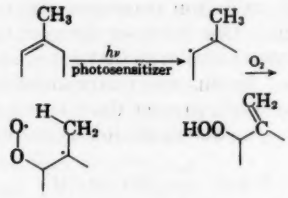
C: R = CH_3
D: = H

compoundC (R = CH_3) is "methyl D" because it is obtained from D (R = H) by heating with methanol and sodium methylate.



V VI

Photosensitized reaction of oxygen with an unactivated double bond apparently involves diradical formation followed by intramolecular hydrogen abstraction.



Formation of a hydroperoxide in this manner will always involve allylic rearrangement and will be favored by dilution.

Degradative Oxidations

The previous sections have described processes by which hydroperoxides, polymeric peroxides, epoxides, alcohols, and carbonyl compounds can be formed as primary oxidation products of autoxidation. All of these products are formed by reactions which are quite simple and easily understood; the only complexity of the reaction scheme results from the number of possible reactions rather than from the complexity of any single step of the reaction. When oxidations are performed under conditions where the initially formed products, particularly peroxidic materials, are unstable the reaction sequence is complicated by still further reactions. For example, by use of elevated temperatures, heavy metal ions, strongly basic or acidic media and high degrees of oxidations the conversion of a methylene group to a carbonyl group or a methyl group to a carboxyl group can be achieved by a combination of radical and ionic reactions. Under conditions where the initially formed peroxides or hydroperoxides decompose readily, products are often formed as a result of radical-radical interactions. Moreover, since alkoxy radicals, acyloxy and acyl radicals are unstable, rupture of carbon-carbon bonds frequently occurs under these conditions.

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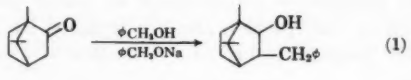

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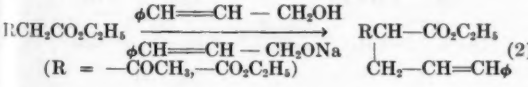

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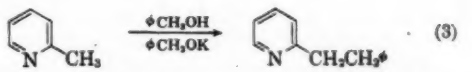

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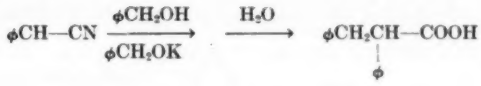

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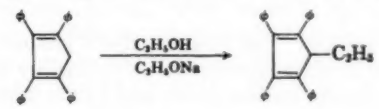

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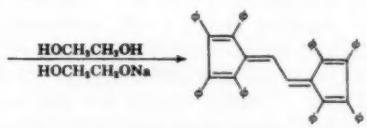

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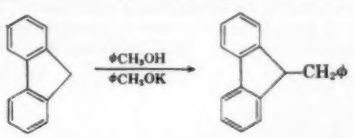

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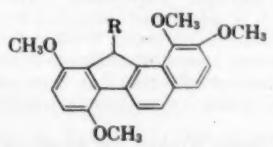
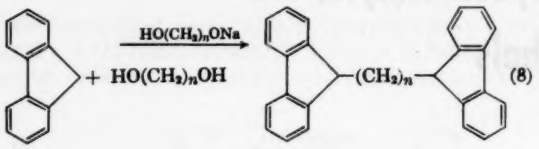


C: R = CH_3
D: = H

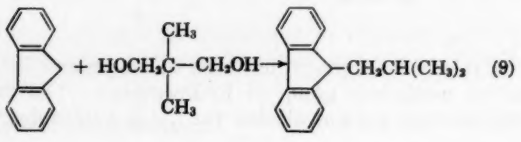
compound C (R = CH_3) is "methyl D" because it is obtained from D (R = H) by heating with methanol and sodium methylate.

Dialkylation, as expected, was observed with ethylene, 1, 2-propylene, tetramethylene, and pentamethylene glycols (equation 8). However, with glycerol the same glycol was obtained as with ethylene glycol. With



(8)

trimethylene glycol, no product was obtained; and with 2,2-dimethylpropan-1,3-diol, only 9-isobutylfluorene was obtained (equation 9) indicating the loss of one carbon atom during the alkylations when the hydroxyl

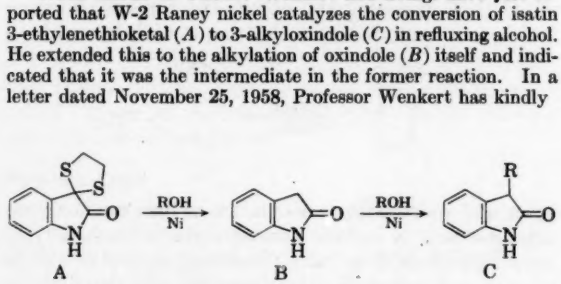


(9)

groups are 1,3. The ethylene glycol product obtained from the glycerol reaction was identified by its melting point, mixture melting point, and by its infrared spectrum which was identical with that obtained less deviously from ethylene glycol itself. 9-Isobutylfluorene was synthesized independently from isobutyl alcohol and was identical with that obtained from 2,2-dimethylpropan-1,3-diol. Possible routes for the loss of the carbon atom will be discussed under Mechanism.[4]

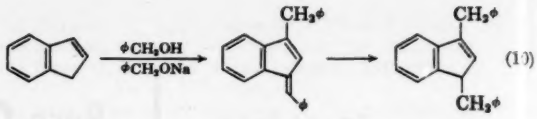
Alkylation of the active methylene groups of hydrocarbons has also been extended to indene, the only hydrocarbon subjected to the reaction which has more than one unsubstituted corner on the cyclopentadienyl ring (*14*). Using benzyl alcohol, two benzyl groups or one benzyl and one benzylidene group are substituted (equation 10).

[4] NOTE ADDED IN PROOF: Wenkert and Bringi have just reported that W-2 Raney nickel catalyzes the conversion of isatin 3-ethylenethioketal (*A*) to 3-alkyloxindole (*C*) in refluxing alcohol. He extended this to the alkylation of oxindole (*B*) itself and indicated that it was the intermediate in the former reaction. In a letter dated November 25, 1958, Professor Wenkert has kindly



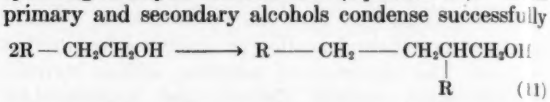
informed me that ethyl malonate is not alkylated with ethanol under these conditions, while ethyl acetoacetate, acetylacetone, and dihydroresorcinol are alkylated in low yield. Although this C-alkylation is not novel, it is indeed interesting that it proceeds under relatively mild conditions. Professor Wenkert feels there is special significance in the mild reaction conditions (letter dated December 11, 1958). However, fluorene has been alkylated with isopropyl alcohol in boiling xylene (reaction temperature 130–140°) (*11*).

I am indebted to Professor Wenkert for supplying results prior to publication. (WENKERT, E., AND BRINGI, N. V., *J. Am. Chem. Soc.*, **80**, 5575-6(1958).)



(10)

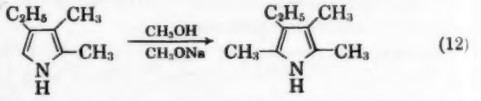
The most generally known of the base-catalyzed reactions is the self-condensation of alcohols (*15, 16, 17*), now called the Guerbet reaction after its inventor. In this reaction two molecules of an alcohol form a dimer by the formal loss of water in such a way as to give a carbon skeleton corresponding to that of the corresponding aldehyde condensation (equation 11). Both primary and secondary alcohols condense successfully



(11)

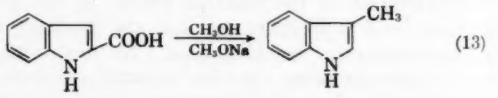
and mixed condensations have also been effected. A more extensive review of the Guerbet reaction has been given recently by Machemer (*18*).

As far back as 1912 the alkylation of pyrrole with ethanol and sodium ethoxide was reported (equation 12) (*19, 20*). The reaction was extended to indole by



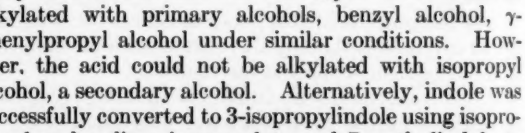
(12)

Cornforth and Robinson (*21*) (equation 13). These authors converted indole and indole-2-carboxylic acid

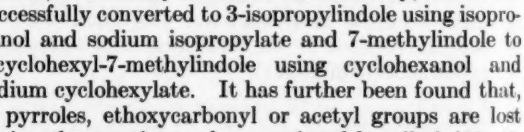


(13)

into skatole using sodium methylate and methanol. They also found that the carboxylic acid could be alkylated with primary alcohols, benzyl alcohol, γ-phenylpropyl alcohol under similar conditions. However, the acid could not be alkylated with isopropyl alcohol, a secondary alcohol. Alternatively, indole was successfully converted to 3-isopropylindole using isopropanol and sodium isopropylate and 7-methylindole to 3-cyclohexyl-7-methylindole using cyclohexanol and sodium cyclohexylate. It has further been found that, in pyrroles, ethoxycarbonyl or acetyl groups are lost during the reaction and are replaced by alkyl (*20, 22, 23*) (equations 14, 15). The deacylation is effective

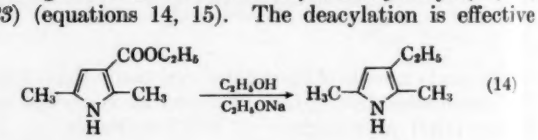


(14)



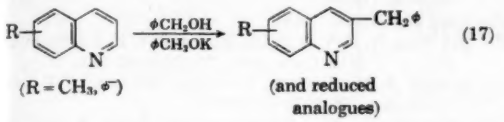
(15)

also with a nitrogen analogue—the ketazine of 2,3,5-trimethyl-4-acetylpyrrole (*19, 24*) (equation 16).



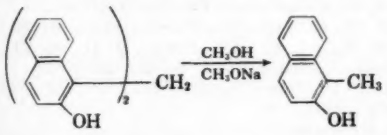
(16)

In a recent paper Sprinzak has reported an unusual alkylation of quinoline in the 3-position (*4*). It has been further shown that a methyl or phenyl in the carbocyclic ring does not inhibit the alkylation (*25*) (equation 17).



(17)

The last category of compounds alkylated with alcohols and their alkoxides are phenols. Resorcinol, phloroglucinol, and 2-naphthol are successfully alkylated with methanol and sodium methylate (*26*). Resorcinol and phloroglucinol are both converted to mesorcin (2,4-dihydroxymesitylene). The yields are improved if the phenol is first converted to a methylene-bis derivative or into an N-piperidylmethyl derivative. In this way 2,2′-dihydroxy-di-α-naphthylmethane gives 75% of 1-methyl-2-naphthol, the best procedure for making this compound (equation 18). The corre-

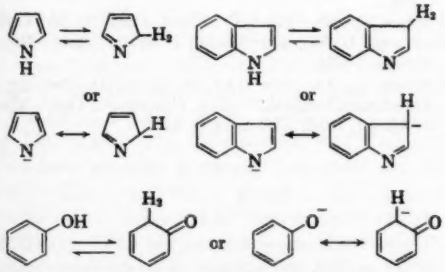


(18)

sponding benzylidene derivative can also be used, in this case giving rise to a mixture of 1-methyl-2-naphthol, 2-naphthol, and 1-benzyl-2-naphthol. 1-(1′-Piperidylmethyl)-2-naphthol, 4-(1′-piperidylmethyl)-1-naphthol, and 2,7-dihydroxy-1,8-bis(1′-piperidylmethyl)phenanthrene all give the corresponding methyl compounds. It is noteworthy that 4-(1′-piperidylmethyl)-1-naphthol gives 4-methyl-1-naphthol since 1-naphthol does not undergo the reaction. The authors also determined that phenol, catechol, and quinol as well as 1-naphthol were recovered unchanged.

The Mechanism of the Reaction

A common structural feature of all of the compounds which can be alkylated is that they contain an active methyl, methylene, or a potential active methylene group. Thus, pyrrole, indole, and phenols fall into this category because of the potential methylene group in the structures:



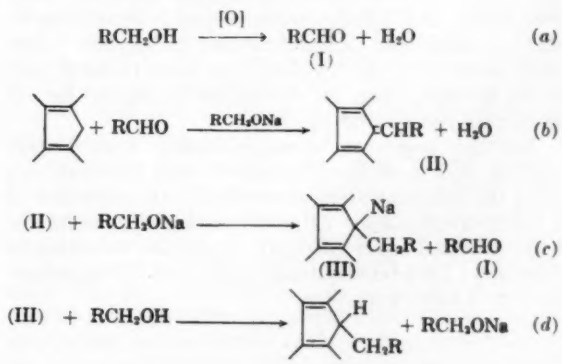
Indeed, it has been shown that 1-methylpyrrole is not alkylated under the usual reaction conditions (*27*). It has also been shown that alcohols with only one alpha hydrogen fail to undergo the Guerbet reaction (*28*). Thus, 2-ethylhexanol gives an ether, but not a Guerbet product. Compounds with an active hydrogen but only one, also fail to be alkylated: 9-alkylfluorenes, triphenylmethane (*28*), monoalkylated ethyl malonate and ethyl acetoacetate. More than one alkyl group can be introduced if the compound may rearrange to give a new potential methylene group. Thus, 3-ethyl-4-methylpyrrole gives 2,3-diethyl-4-methylpyrrole and 2,3,5-triethyl-4-methylpyrrole (*20*), but no more than one alkyl group is introduced per carbon atom in the ring and no alkyl group is introduced on the nitrogen. It has also been found that 1,2,3,4-tetraphenylfulvene, a related molecule, is reduced with sodium ethylate or butylate under the same conditions to 5-methyl-1,2,3,4-tetraphenylcyclopentadiene (*30*).

A base is required for the reaction. Guerbet's early work established this point. This may be questioned with amines, since added base is not always employed (*31*); however, the amine may serve as its own base. In the alkylation of fluorene, need for a base has been established (*12*).

Recently, the alkylation of aniline has been shown to be catalyzed by finely divided nickel (*31*, *32*, *33*, *34*, *35*). It was elegantly demonstrated by Rice and Kohn (*32*) that alkylation necessarily followed the dehydrogenation of the alcohol. Only under a high enough temperature, as demonstrated in separate reactions, to convert alcohol to aldehyde, would alkylation take place. Nickel also catalyzes the alkylation of hydrocarbons (*11*, *13*, *14*).

From the standpoint of the alcohol, it is necessary that the alcohol can be oxidized to an aldehyde. Thus, *tert*-butyl alcohol does not alkylate indole-2-carboxylic acid (*21*) nor 1,2,3,4-tetraphenylcyclopentadiene (*7*). However, triphenylcarbinol does alkylate ethyl malonate (*3*).

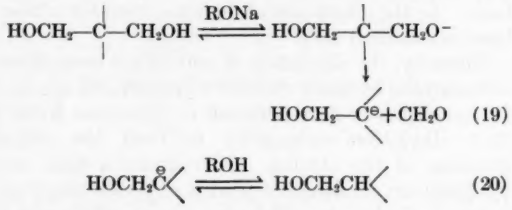
The sum total of the facts cited are consonant with the following mechanism first stated by Cornforth, Cornforth, and Robinson (*26*) for the alkylation of phenols, by Weizmann, Bergmann, and Sulzbacher for the Guerbet reaction (*28*), by Pratt and Frazza for aniline (*31*), by Sprinzak (*8*) and by Schoen and Becker (*10*) for pentagonal hydrocarbons:



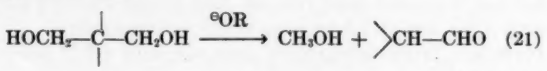
Equation (*a*) represents the adventitious oxidation of the alcohol under the reaction conditions, (*b*) represents a base-catalyzed condensation of the aldehyde with the active methylene group, (*c*) is patterned after well-known metal-alkoxide interconversion of polarized bonds, carbonyl groups with alcohols. A more usual example is that (II), the unsaturated intermediate, can take part in this reaction because it is a dipolar molecule (*36*). Reaction (*d*) merely completes the

equilibrium, a reasonable step because of the general greater acidity of alcohols versus hydrocarbons.

Since an unsaturated intermediate is required, this scheme accounts for the failure to dialkylate active methylene groups. It thus accounts for the pure monoalkylation using this procedure as opposed to the alkylation with alkyl halides which always gives some dialkyl product. The first step makes it possible to account for the loss of one carbon atom and the monoalkylation with 1,3-diols. Here the oxidation would produce a β-hydroxyaldehyde, i.e., an aldol. In the presence of base the aldol may reverse to give formaldehyde and isobutyraldehyde which could enter into step (*b*). Searles and Ives (*37*) have proposed that the anion of the diol goes to methanol and an aldehyde (equations 19, 20). This mechanism appears to be



credible for cyclic 1,3-glycols and for those glycols with two large substituents at the middle carbon. A third alternative is the possible direct loss of methanol (equation 21).



Although direct evidence for the three alternatives is not available for the general case, the author feels that the first is the most feasible with some possibility of the second for highly substituted diols.

An explanation for the failure to produce an alkylated product with 3-dialkylamino-1-propanol is not readily forthcoming. Boiling of the aminoalcohol is accompanied by the evolution of the dialkylamine (*13*). It is well known that 3-dialkylaminopropanols decompose to dialkylamines and α,β-unsaturated aldehydes. Further reaction of the acrolein with base to form tars could account, then, for the failure to obtain the expected alkylated product.

For the origin of 3-benzylquinoline from benzyl alcohol and quinoline, Avramoff and Sprinzak (*4*) cited the following steps as probable: (1) reduction to 3,4-dihydroquinoline; (2) condensation with benzaldehyde (oxidized benzyl alcohol); (3) further reduction to 3-benzyl-1,2,3,4-tetrahydroquinoline; or (4) rearrangement to 3-benzylquinoline.

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News of the publication by Farnsworth Books, Boston, of "One Pearl of Great Price" is not exactly of the man-bites-dog variety, but almost. The author, W. F. Luder, known to readers as a frequent contributor to these pages and now a member of the Editorial Board, has written a historical novel. The setting is the fast-moving world of first century Christianity. Both events and ideas are recounted in a way that keeps the reader on his mental toes.

Robert Neilson Boyd
New York University,
New York, N. Y.

Electrochemistry of Organic Compounds

A survey course for chemistry seniors

There is a need for a good survey course for chemistry seniors, one that will really tie together all the branches of chemistry they have studied, one that will bring in physics, mathematics, and possibly even the use of German. What is needed is a course that will correlate *and use* inorganic, organic, analytical, and physical chemistry; that will bring in instrumentation, thermodynamics, atomic and molecular structure, theoretical as well as applied chemistry, stereochemistry, radioactivity; that will see to it that students go to the literature. We need a course that offers another chance (hopefully, not the first!) for students to follow the development of ideas in chemistry and see how concepts undergo changes on the basis of facts.

I should like to suggest such a course: "Electrochemistry of Organic Compounds." The title has been chosen with deliberate intent. It is definitely not "Organic Electrochemistry," a name associated with synthetic applications; nor is it just plain Electrochemistry, since such a title would most certainly give the wrong impression. The course is built around organic compounds, as the name shows, and the emphasis is placed upon them so that "straight" physical chemistry does not pre-empt the course, nor does instrumental detail, nor does analytical application. The course need not necessarily be a survey of all aspects of electrochemistry, but rather of those aspects which serve best to unify the field of chemistry—in review and in extension.

The course is suggested here for seniors, but it can also be used as the basis of an advanced graduate course, where the need for integration is at least as great as in the undergraduate curriculum.

A one-semester course in the electrochemistry of organic compounds has been given at New York University since 1953. There are two hours of class per week, although three hours would probably be better. There is no text yet available, since the books now on the market are too specialized, e.g., those by Lingane (*1*), Kolthoff and Lingane (*2*), Meites (*3*), Martell and Calvin (*4*), Bailar (*5*), Swann (*6*), and Delahay (*7*). So literature sources primarily are used for reading material. Each student is given a list of pertinent references and is expected to read a considerable number of them. The references form the basis of class discussion, and quite a number are taken up in some detail, giving the student a chance to check his comprehension of the papers. This enables the accomplishment of one more aim of the course: the student's gaining a familiarity with the literature of chemistry and learning how to read and use it. A number of students have expressed delight that as a result of all this reading they got over their fear of the journals and acquired the confidence to tackle, on their own, papers that they would have otherwise avoided.

As conducted, the course is mostly reading, lecture, discussion in class, problems, and a written examination. There is no obvious hindrance, however, other than perhaps that of time in a two-hour course, to the assignment of a term paper, or reports in class, or quizzes on designated readings. Lectures are illustrated by slides, and by numerous drawings of curves from the literature. These are enlarged on paper beforehand by means of a pantograph, since many interesting and important curves are often difficult to draw quickly on the blackboard with enough accuracy and detail to be meaningful.

Course Content

Organization of the material of the course has been around four major subjects: electrolysis, potentiometry, polarography, and chelate compounds. Some readers may look in vain for certain items in what follows. They must accept several limitations: (*a*) It is not the aim of the course to provide an exhaustive treatment of electrochemistry. (*b*) The length of this paper will not permit the mention of every topic, e.g., coulometry and amperometric titrations. (*c*) There has just not been enough time in a two-hour course to do justice to such topics as conductivity and nuclear magnetic resonance. A three-hour course should enable inclusion or expansion of such topics.

Electrolysis was chosen as the initial subject for several reasons: Historically, it is first; an organic tone can be set early (to balance the inevitable reliance on physical chemistry); it is a relatively straightforward topic (compared to most other aspects of electrochemistry, that is). Specifically, after a review of fundamentals of electrolysis, one might start with the Kolbe electrolysis of carboxylic acids. The apparatus is the height of simplicity, much excellent work has been done recently (*8*); a review of the reaction is available (*9*); considerably more is known about its mechanism than about most electrolyses (*10*). It is an admirable choice for demonstrating the usefulness in synthetic work of that most elegant of reagents, the electron. With little difficulty an enthusiastic acceptance of electrochemical methods can be built up. It is possible, before finishing the Kolbe reaction, to bring up free radical mechanisms and to review stereochemical sub-

Presented before the Division of Chemical Education, at the 133rd Meeting of the American Chemical Society, San Francisco, April, 1958.

jects such as loss or retention of configuration, *meso* compounds, etc.

A brief look at the oxidation of sugars to glyconic acids offers a chance for review of carbohydrate chemistry; and electrochemical fluorination, another anodic process, introduces the student to the increasingly important perfluoro compounds.

Cathodic electrolysis of carbonyl and nitro compounds is presented next. Subjects taken up include overvoltage, current density versus electrode potential, potentiostats and constant potential reductions (*11*, *12*, *13*), and rationalization of electrolytic procedures by polarographic techniques (*11*, *14*). The last requires a discussion of electrolysis and polarization, which can be accomplished earlier (if desired) in the introductory review of electrolytic principles. Use of polarography here foreshadows its appearance in a later part of the course. Finally, modern and older ideas about electrolytic reduction are contrasted: "nascent hydrogen" versus the idea that the electrons and protons come from different sources (*15*). Discussion of the reduction of a quinone to a hydroquinone by way of one-electron steps through the semiquinone can provide a bridge to the next major section of the course.

Potentiometry, the second part of the course, is devoted largely to the study of quinone-semiquinone-hydroquinone systems, since these are the most significant reversible organic oxidation-reduction systems. Before plunging into the organic aspects, it is probably advisable to review the fundamentals of potentiometry by means of inorganic examples. The article by Delahay, Pourbaix, and van Rysselberghe (*16*) may give an interesting new twist to the subject for most students. The plotting of one or more of the Pourbaix potential-*p*H diagrams (e.g., the Cr-Cr(III)-Cr(VI) system), and seeing how they can be used to calculate such equilibrium constants as K_{sp} for chromium hydroxide or K_{eq} for the transformation of dichromate ion into chromate ion, will provide a valuable background for the understanding of potential-*p*H diagrams derived from the potentiometric titrations of quinones (*17*). It will probably be found necessary to take an excursion into *p*H and redox titrations characteristic of quantitative inorganic analysis. It will be time well spent, since a knowledge of these principles is fundamental also to the fourth major division of the course, chelate compounds.

A study of the potentiometry of quinones involves a student's reviewing and strengthening his hold on thermodynamics, free energy, entropy, equilibria, tautomerism, resonance, paramagnetism, and structural theory. Before he gets through he should know more about free radicals from Michaelis' work on semiquinones (*18*), and have some appreciation from more recent work (*19*) of their importance in biological (enzyme-catalyzed) redox systems.

If there is time, this might be the point at which to take up nuclear magnetic resonance (NMR) and electron spin resonance (ESR) and their use in modern research.

Polarography. The transition from potentiometry to polarography, the third major division of the course, is an easy one. It may be found most convenient to develop the fundamentals of polarography with illustrations from the field of inorganic chemistry, while many of the most interesting examples of the use of the polarographic technique involve organic compounds.

The study of polarography provides an opportunity to take up analytical methods, both inorganic and organic. It also permits a second look at: (1) the use of polarography as a pilot technique in preparative electrolyses (*11*, *14*), especially in irreversible systems; 2) constant potential reductions (*11*, *12*, *13*); (3) the mechanisms of cathodic reductions; (4) what can be deduced from the shapes of curves; (5) polarization and overvoltage; (6) semiquinones.

The difficult part of a study of polarography is to know where to stop since there is so much material available. But one can slide smoothly into the fourth major division of the course, chelate compounds, since polarographic (and potentiometric) methods have been used so extensively in investigations of these interesting and significant substances.

Chelate Compounds. All of a student's training in chemistry can be brought to bear on the subject of chelate compounds. The simultaneous application of inorganic, organic, analytical, and physical chemistry to a single problem can be to a student a vivid illustration of the essential unity of chemistry, a reminder that he no longer need—nay, must not—keep these various branches separate, even though he has been up to now graded on each individually.

Handled properly, the subject of chelate compounds can bring to a focus modern thought on: (1) atomic and molecular structure; (2) the periodic table and its manifold significance; (3) hybridization of orbitals and stereochemistry; (4) radiochemistry; (5) kinetics; (6) equilibria; (7) stabilization of unfamiliar valence states; (8) practical application and theoretical considerations; (9) new analytical techniques; etc. One can also relate to chelate chemistry much of the fundamental material met earlier in the course. All in all, chelate compounds provide a fitting climax to the course and to the purpose for which it is designed: (*a*) a survey that will tie together the entire field of chemistry, and (*b*) a course that will give the student a fresh viewpoint and open up new areas of study, interest, and research.

Obviously the bare bones have to be fleshed out, but the foregoing may give some idea of what has been done in one course, and a prospect of what might be done in others.

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Variation of the Solubility Product Constant with Ionic Strength

In the course of his first two years in college, the chemistry student continually encounters new concepts that are not immediately apparent or understood. In spite of the fact that a new concept may be the result of a mathematical derivation or of a logical development, the student may well have some reservations concerning the new idea until it has been clearly proved to him by a lecture demonstration or by a laboratory experiment. This is particularly true when the new concept appears to contradict what the student learned during the previous year. The constancy of the solubility product (particularly for the 1–2 and 2–1 valence types of salts, the solubility products of which include squared factors) and its variation with ionic strength and particle size, are all concepts which, from the writer's experience, many students accept partly "on faith" rather than from complete conviction.

For a number of years the writer has searched for a simple experimental method for demonstrating, either by lecture or by laboratory experiment, the truth and reality of one or more of these concepts. Recently R. W. Ramette[1] suggested three experiments in solubility (involving silver bromate, calcium sulfate, and lead sulfate) by which the solubility product and its relationship with ionic strength can be determined experimentally by students of elementary quantitative analysis. Each of these experiments involves the saturation of the solution with the pure salt in the usual manner and the determination of the concentration of the particular ion by standard methods of volumetric analysis, and requires one or two laboratory periods for completion.

Several years ago during the course of a lecture demonstration that involved the precipitation of cadmium iodate, unexpected results were obtained. When a 0.2-molar solution of cadmium nitrate was added to a test tube containing potassium iodate of the same molarity, a permanent precipitate was formed upon the addition of one or two drops. When the solutions were reversed no permanent precipitate was formed until after several ml of the potassium iodate solution had been added. These results rather strikingly demonstrate that the concentration of the iodate ion plays a more important role in the precipitation of cadmium iodate than that played by the concentration of the cadmium ion. It occurred to the writer to study the possibilities of carrying out the reaction as a titration using quantitative methods. This study has resulted in the development of: (*a*) a simple lecture demonstration of the constancy (under the right conditions) of the concentration solubility product and the effect of particle size on solubility, and (*b*) a relatively simple laboratory experiment for quantitatively demonstrating the effect of the ionic strength on the concentration solubility product.

$$K_s = (Cd^{++})\,(IO_3^-)^2$$

The reaction was found to be well suited for a titration in which the end point is indicated by the production of a permanent cloudy precipitate. In order to reduce the possibilities of the formation of large crystals in the precipitate the titration vessel should have a wide mouth and be free from scratches on the inside. A 250-ml wide-mouth Erlenmeyer flask was found to be satisfactory. The relative precision obtainable in the titration depends not only upon the volume of the titer solution but also upon the sharpness of the end point, which deteriorates markedly at concentrations below 0.1 molar. When cadmium nitrate is the titer solution, optimum precisions (approximately 2%) are obtained with a cadmium nitrate concentration of 0.1 molar and a potassium iodate concentration of 0.3 molar. When the potassium iodate is the titer solution, precisions somewhat better than one per cent are possible over a wide range of concentrations.

The cloudy precipitate is stable for fifteen minutes or longer. If the mixture is allowed to stand at constant temperature for an hour it will eventually clear with the formation of a relatively large quantity of cadmium iodate crystals in the bottom of the flask. This might appear to suggest that a supersaturated solution exists at the end point. This is not the case.

[1] Ramette, R. W., J. Chem. Educ., **33**, 611 (1956).

Just before the end point is reached the colloidal precipitate dissolves rather quickly. At the end point, therefore, the particles of colloid size are in true equilibrium with the solution. Upon standing, the larger particles grow at the expense of the smaller ones. The larger particles thus produced are not in equilibrium with the solution and further growth of these particles takes place. Eventually the large increase in the size of the particles will result in a relatively large decrease in the solubility of the salt and considerable salt will crystallize out of the solution. The effect is magnified by the fact that the solubility of the cadmium iodate is decreased further by the accompanying decrease in the ionic strength of the solution.

The selection of cadmium iodate for this study was fortuitous. The precipitation characteristics of eight other comparably soluble salts (copper fluoride, silver sulfate, silver bromate, silver acetate, lithium phosphate, lead chloride, copper iodate, and cadmium tartrate) were investigated. All of these with the exception of cadmium tartrate showed high supersaturation tendencies, and sharp end points were not obtainable.

The Demonstration

The lecture is opened with the reciprocal titrations of solutions of KIO_3 and $Cd(NO_3)_2$ at equal molarities, the end point in each case being the first appearance of a persisting colloidal precipitate. The results of one such pair of titrations are shown in the first two lines of Table 1 The apparent discrepancy between the

Table 1. Reciprocal Titrations at Equal Molarities ($Cd(NO_3)_2$ and KIO_3 both 0.2 Molar)

Conditions for first appearance of persisting precipitate, $Cd(IO_3)_2$→	KIO_3 added to $Cd(NO_3)_2$	$Cd(NO_3)_2$ added to KIO_3
Volume (ml) KIO_3 solution	34.85	100.0
Volume (ml) $Cd(NO_3)_2$ solution	100.0	2.00
Concentration (moles/l) Cd^{++} present	0.148	0.00392
Concentration (moles/l) IO_3^- present	0.0517	0.196
Ion product $(Cd^{++})(IO_3^-)^2$	4.0×10^{-4}	1.5×10^{-4}
Ionic strength	0.496	0.208

two results is usually a source of some wonder on the part of students until it has been explained in terms of the law of mass action and equilibria involving squared factors. The concentrations of the Cd^{++} and I_3O^- ions at the end points are evaluated and used to calculate the corresponding concentration solubility products.

The discrepancy between the two calculated values of solubility product is explained by a consideration of the activity and ionic strength concepts (as developed by Lewis and Randall)[2] as follows:

The activity, a is defined as the "effective" concentration of an ion, and the activity coefficient, f, is then defined by the equation

$$f_i = a_i/m_i \qquad (1)$$

where m_i represents the molar concentration of an ion. The "true" or thermodynamic solubility product, K_t, is distinguished from the classical solubility product constant,

$$K_c = (Cd^{++})(IO_3^-)^2 \qquad (2)$$

and is defined by the equation,

$$K_t = (a_{Cd^{++}})(a_{IO_3^-})^2 \qquad (3)$$

This may be written in terms of the molarities and activity coefficients,

$$K_t = (m_{Cd^{++}})(m_{IO_3^-})^2 (f_{Cd^{++}})(f_{IO_3^-})^2 \qquad (4)$$

The mean activity coefficient is defined as

$$f = (f_{Cd^{++}} f_{IO_3^{-2}})^{1/3} \qquad (5)$$

and equation (4) may then be written

$$K_t = K_c f^3 \qquad (6)$$

The concept of ionic strength is introduced and defined by the equation

$$\mu = \Sigma \frac{(m_i z_i^2)}{2} \qquad (7)$$

where z_i is the charge on a given ion. This is followed by the generalization of Lewis and Randall[2] that "in dilute solutions the activity coefficients of a given strong electrolyte are the same in all solutions of the same ionic strength." Accordingly, the values of K_c may be expected to be the same only in solutions of the same ionic strength. The ionic strengths of the mixtures at the end point of the demonstrated titrations are calculated and the difference noted. To illustrate the calculation of the ionic strength of a solution the first end point mixture is taken as an example. The molarity of each ion is multiplied by the square of its valence or charge:

$$\begin{aligned} \text{For } K^+ &: (0.196)(1)^2 = 0.196 \\ \text{For } IO_3^- &: (0.196)(1)^2 = 0.196 \\ \text{For } Cd^{++} &: (0.00392)(2)^2 = 0.015 \\ \text{For } NO_3^- &: (0.00784)(1)^2 = 0.008 \\ & \qquad\qquad\qquad\quad 0.425 \end{aligned}$$

For which the ionic strength is:

$$\mu = \frac{0.425}{2} = 0.213$$

A second pair of reciprocal titrations is demonstrated. This time solutions of KIO_3 and $Cd(NO_3)_2$ of equal ionic strengths are used in order to produce final equilibrium mixtures also having equal ionic strengths. The results of such a pair of titrations, as shown in Table 2, demonstrate the constancy of the classical solubility product under these conditions.

Table 2. Reciprocal Titrations at Equal Ionic Strengths ($Cd(NO_3)_2$, 0.1 Molar and KIO_3, 0.3 Molar)

Conditions for first appearance of persisting precipitate, $Cd(IO_3)_2$→	KIO_3 added to $Cd(NO_3)_2$	$Cd(NO_3)_2$ added to KIO_3
Volume (ml) KIO_3 solution	20.55	100.0
Volume (ml) $Cd(NO_3)_2$ solution	100.0	2.60
Concentration (moles/l) Cd^{++} present	0.0830	0.00252
Concentration (moles/l) IO_3^- present	0.0510	0.290
Ionic strength	0.300	0.300
Ion product $(Cd^{++})(IO_3^-)^2$	2.2×10^{-4}	2.1×10^{-4}

As a final point in the demonstration, attention is called to the flask which contains the end point mixture from the first titration, which by this time will contain a relatively large amount of crystals of cadmium iodate. The titration of this mixture with cadmium nitrate solution is then continued. The cadmium iodate crystals of colloid size thus produced are quickly redissolved in the solution although at the same time it is in equilibrium with crystals of macro size.

[2] Lewis, G. N., and Randall, M., *J. Am. Chem. Soc.*, **43**, 1112 (1921); "Thermodynamics and the Free Energy of Chemical Substances," McGraw-Hill Book Co., Inc., New York, 1923.

This furnished a dramatic demonstration of the effect of particle size on solubility and lends conviction to a discussion of the theory of supersaturation and the aging of precipitates. One now may point out the difference between the experimental values of K_c and the value, 1×10^{-6}, which is obtained by calculation from the solubility measurements of Oelke and Wagner[3] in which macro-size crystals of cadmium iodate were used.

The Experiment

The experimental study of the *quantitative* relationship between the concentration solubility product and the ionic strength is performed by students in the laboratory. In lecture the interionic attraction theory is discussed and the Debye- Hückel equation,

$$\log f = \frac{-A_s{}^{+}z^{-}\mu^{1/2}}{1 + aB\mu^{1/2}} \qquad (8)$$

introduced and the significance of the several terms explained. This for cadmium iodate at 25°C becomes (approximately):

$$\log f = \frac{-1.02\,\mu^{1/2}}{1 + \mu^{1/2}} \qquad (9)$$

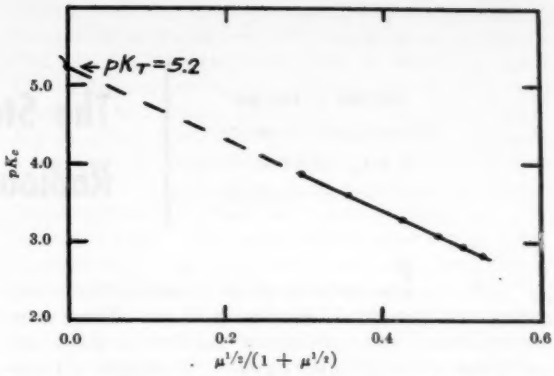
Substituting the value for log f into the logarithmic form of equation (6),

$$\log K_c = \log K_t + \frac{3.06\,\mu^{1/2}}{1 + \mu^{1/2}} \qquad (10)$$

which may be written

$$pK_c = pK_t - \frac{3.06\,\mu^{1/2}}{1 + \mu^{1/2}} \qquad (11)$$

This suggests that if the experimental values of pK_c are plotted against the complex ionic strength function, $\mu^{1/2}/(1 + \mu^{1/2})$, the result should be a straight line with a y-axis intercept at pK_t.



Variation of pK_c with ionic strength. Temperature = 25°C. Data of Donna Karasek.

In the laboratory the students titrate 100-ml samples of (already prepared) standard solutions of cadmium nitrate, at concentrations ranging from 0.05 to 0.5 molar, with a 0.300 molar solution of potassium iodate. The several values of pK_c and μ are calculated and the results plotted as shown in the figure. The particular curve shown was derived from data obtained by a student in the course of a regular two-hour laboratory period. The value of K_t obtained by extrapolation is considerably higher than that obtained by F. Saegusa,[4] 2.3×10^{-6}, from equilibrium studies using *macro-sized* crystals of cadmium iodate. This is in accord with the results obtained in the lecture demonstration.

[3] Oelke, W., and Wagner, C., *Proc. Iowa Acad. Sci.*, **46**, 187 (1939).

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Titrimeter for Sulfur-Containing Gases

Most viewers of TV have at one time or another been exposed to a commercial in which a "mysterious marvelous machine" of science measures the odor of onion. A needle swings far in one direction, only to be returned to zero by the introduction of some material purported to cut down odors in the mouth and respiratory areas. Few viewers realize that the instrument in use is a descendant of an early model developed by the Army Chemical Corps as a recording titrimeter to monitor the concentration of mustard gas in the atmosphere during tests of protective clothing.

Dr. J. H. Northrup (Nobel Prize for Chemistry, 1947) developed the original device which involved a titration of mustard gas with bromine, the end point being determined potentiometrically. Dr. Philip A. Shaffer (NDRC) improved the design and increased the sensitivity down to 0.1 ppm by providing for the generation of the bromine by electrolysis of KBr within the potentiometric cell. Further developments have been incorporated by Consolidated Engineering Corp. in the currently available "Titrilog." The bromine-generating current which is directly proportional to the amount of oxidizable sulfur present in the sample is recorded on a strip chart.

The value of this tool for peacetime industrial applications is one more illustration of Chemical Corps contributions to safeguarding life and health. The automatic titrimeter is indispensable in smog studies and in all public health monitoring of atmospheres contaminated by H_2S, SO_2, or other sulfur-containing gases.

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The Statistics of Radioactivity Measurement

The disintegration of radioactive atoms occurs in a completely random manner. There is no way by which one can forecast the time at which any particular atom will disintegrate. A sample of radioactive material may have a true average disintegration rate of perhaps 100 disintegrations per minute. It is improbable, however, that exactly 100 disintegrations occur in any one minute. Indeed, if one reasons without recourse to precise probabilities it might appear likely that in one minute the sample would have only a few disintegrations, in the following minute several hundred disintegrations, and only after a sufficiently long time, an average of 100 disintegrations per minute. By the application of statistics, we may determine the probability with which the observed rate corresponds to the true average rate of disintegration of a radioactive sample.

This paper attempts to provide a unified discussion of the statistical considerations fundamental to radiation counting. It is intended to supplement and provide illustrative examples for the material covered in reference textbooks frequently consulted by chemists (*1*, *2*, *3*).

Statistical Error as a Function of the Total Count

Although the recorded number of counts is usually only a fraction of the total number of disintegrations, the probability of recording any count is governed by the same relation that governs the probability of occurrence of the disintegrations. This probability is given by the Poisson distribution[2] (see Table 1 for notation).

$$P(n) = \frac{e^{-r}r^n}{n!} \qquad (1)$$

The probability of recording a certain count is dependent solely on the total number of counts, not on the rate of counting.

Problem. A certain sample has a true average counting rate of 20 counts per minute. What is the probability that 10 counts be obtained in a one-minute recording?

Answer. Upon inserting the proper values in equation (1)

$$P(n) = \frac{10^{-20/2.3} \times 20^{10}}{1 \times 2 \times 3 \ldots 10} = 0.0058$$

On the average, out of every 1000 measurements, about six will have a value of 10 counts.

When the number of recorded counts is small, the probability of obtaining a count a few units greater than the true average count is not the same as the probability of obtaining a count the same number of units less than the true average count. Thus, if the true average count is 4, a count of minus 1 will never be observed, whereas a count of plus 9 will be observed in 13 out of 1000 measurements. The distribution is not symmetrical. However, if the number of counts is large, the probability of recording a count equal to the true average count plus a relatively small number of counts, becomes essentially the same as the probability of recording a count equal to the true average count minus the same number of counts. The distribution becomes symmetrical and as such it may be expressed as a Standard, or Gaussian distribution (*5*).

$$G(n) = \frac{1}{\sqrt{2\pi r}} e^{-q^2/2r} \qquad (2)$$

Because simpler formulas may be used, statistical error of counting is usually expressed on the basis of this distribution, rather than of the Poisson distribution.

In the measurement of radioactivity, we are usually not interested in knowing the probability of obtaining some single value, as expressed in equation (1) or (2), but rather knowing with what probability our recorded value is within a certain number of counts, or a certain percentage, of the true value. An equation for such a relation may be derived (*4*) from equation (2) and then placed in the form,

$$q = K\sqrt{r}, \text{ where} \qquad (3)$$

q is the deviation from the true average count within which there is a certain probability that the recorded value falls,

K is a number which corresponds to, but itself is not, (see Table 2) a probability that any one determination will fall within q. Stated in other terms, it corresponds to the fraction of successive determinations which should fall within q. It is referred to as "the number of standard deviations" and

Table 1. Notation Followed in This Article[a]

e	= base of natural logarithms
m	= number of experimental samples counted
n	= observed number of counts
q	= deviation from the true average count
r	= true average count, or the mean of a large number of counts
Subscripts:	
b	= background
s	= sample including background
y	= sample corrected for background
F	= fractional error
K	= number of standard deviations
N	= cpm = counts per minute or per unit time
Q	= q/t = deviation from the mean count in counts per unit time
R	= true average count per unit time, or the mean of a large number of measurements
c	= t_b/t_s
k	= N_s/N_b

[a] After JARRETT (*4*).

[1] Department of Physiological Chemistry.

[2] This equation, as well as the others presented in this paper, may be applied only when the half life of the isotope being measured is long in comparison with the time devoted to measurement. If a radioactive daughter is formed by decomposition of the parent isotope, the half life of the daughter should also be long in relation to the time of measurement.

the probability to which it corresponds is called the "confidence limit,"
r is the true average count.

When K in equation (3) is 1, q becomes the standard deviation of random distribution. This means that in a large number of measurements of the same sample, 68.3% (confidence limit = 0.683, Table 2) of the measurements should be in error by less than the square

Table 2. Confidence Limits Corresponding to K and Representative Errors When Total Counts Are 100 and 1000

K (Number of standard deviations)	Confidence limit corresponding to K	Error (in %) when total[a] count is 100	1000
0.50	0.383	5.0	1.58
0.68	0.500	6.8	2.14
0.80	0.576	8.0	2.53
1.00	0.683	10.0	3.16
1.20	0.770	12.0	3.80
1.40	0.840	14.0	4.43
1.65	0.900	16.5	5.20
1.81	0.930	18.0	5.69
1.96	0.950	19.6	6.20
2.33	0.980	23.3	7.36
2.58	0.990	25.8	8.14
3.00	0.997	30.0	9.49

[a] If the measurement is repeated many times, the fraction of the measurements represented by the confidence limit will be in error by less than the recorded error.

root of the true count; 31.7% of the measurements should have a larger error. When K in equation (3) is 2, about 95% (Table 2) of successive measurements should be in error by less than twice the square root of the true average count.

Problem. Repeated measurements are made on a radioactive sample whose true average count is 920. Within how many counts should 90% of the measurements fall?

Answer. Ninety per cent corresponds to a K value of 1.65 (Table 2). Upon inserting in equation (3),

$$q = 1.65\sqrt{920} = 50$$

Of repeated measurements, 90% should fall within 900 ± 50 counts.

In practical work, the true average count, r, of equation (3) is not known and it is necessary to substitute for it, n, the observed count. The error introduced by this substitution is small when one deals with the large number of counts used in measurements of radioactivity. Also, it is usually desired to express the deviation as a fractional or percentage deviation, rather than as the number of counts deviation. Upon substituting n for r and dividing equation (3) by n,

$$F = K/\sqrt{n} \qquad (4)$$

This equation gives the fractional error within which there is a certain probability (the confidence limit) that the measurement will fall, when n counts are recorded. It may be used to determine any one of these factors when the others are known.

Problem. It is desired to measure a sample with such statistical accuracy that the chances are 1 out of 2 that the measurement is within 1.0% of the true value. How many counts must be taken?

Answer. A probability of 1 out of 2 (0.5 confidence limit) corresponds to a K value of 0.68 (Table 2). Upon rearranging equation (4) and substituting,

$$n = K^2/F^2 = 0.68^2/0.01^2 = 4624$$

For this degree of accuracy, 4624 counts must be taken.

Errors of measurement are usually expressed in terms of the probable error, the standard deviation, the 0.90, the 0.95, or the 0.99 error or confidence limit. The probable error and the standard deviation correspond to the 0.5 and 0.68 errors, or confidence limits, respectively. Each number is the fraction of successive determinations which should fall within the stated error, or expressed in another way, each of these numbers is the probability that any one determination lies within the stated error. The numbers correspond to K values of about 0.68, 1.00, 1.65, 1.96, and 2.58, respectively. The standard deviation is used more often than any other confidence limit, perhaps because it is obtained very easily, by simply taking the square root of the recorded number of counts. It should be noted that the term standard deviation is used here in place of the term standard error. Standard deviation refers to deviations in the original observations, as do the other errors mentioned here, whereas standard error refers to deviations in the means of series of original observations.

Statistical Error as a Function of the Counting Rate

A measurement of radioactivity is usually made over an interval of longer than a minute and then expressed as counts per minute, or, as a fractional or percentage error. In order to express the error in terms of counts per minute, Nt is substituted for r in equation (3) and the equation is divided by time in minutes, to give,

$$Q = K\sqrt{N/t} \qquad (5)$$

In order to express the error as a fractional error, equation (5) is divided by N, (or Nt is substituted for n in equation (4)).

$$F = K/\sqrt{Nt} \qquad (6)$$

When the counting rate is determined as the mean of a series of similar determinations, the deviation of the mean of the series is equal to the deviation of a single determination divided by the square root of the number of determinations. Thus if a measurement is made 9 times and the 0.95 error of a single measurement is 10%, the error of the mean of the 9 measurements is $10 / \sqrt{9} = 3.3\%$.

The Error Introduced by the Background

In the experimental determination of the counting rate of any sample, the counting rate of the background is included in the counting rate of the sample. The errors discussed so far apply to this total counting rate. Because of the variation in the counting rate of the background, the fractional error of the counting rate of the sample corrected for the background is always larger than the fractional error of the recorded rate of the sample including the background. We become interested in the error of the counting rate of the radioactive sample corrected for background as it may be calculated from the total counting rate and the counting rate of the background.

The Optimum Distribution of the Time Between the Counting of the Sample and the Background. When the background count is small in comparison with the count of the sample, the fraction of the total time given to the counting of the background should be small. Thus,

in the limiting case of no background count, no time is devoted to its measurement. When the total count is close to the background, the time devoted to the background should approach that devoted to the sample. Whenever a determination of the background is used for the correction of the counting rate of a single sample, the most efficient distribution of time between the counting of the background and the sample may be shown to be equal to the square root of the ratio of the counting rate of the background to the rate of the sample. If the counting rate of a certain sample is 100 and the background is 25, twice as much time should be devoted to counting the sample as to the background.

Usually, when counting rates are measured, a number of samples are corrected for the same background. For the most efficient distribution of time, the time devoted to the background must be then greater than the time required when one sample is measured, but less than the sum of the times required if each background is determined independently. If the samples measured all have about the same activity and are measured for the same length of time, the optimum division of time between the background and each of these samples may be shown to be,

$$t_b/t_s = \sqrt{mN_b/N_s} \qquad (7)$$

where t_s is the time devoted to the measurement of a representative sample and m is the number of experimental samples measured not including the background. If four different samples, each counting about 100 cpm are corrected for a single background of 25 cpm, as much time should be devoted to the background as to each sample (also see Table 3).

Table 3. The Optimum Distribution of Counting Time Between Background and Samples[a]

Ratio of counting rate of sample to background	Time devoted to counting the background per unit time devoted to a representative sample, when the number of samples is				
	1	2	5	10	20
1.25	0.9	1.3	2.0	2.9	4.0
2.0	0.7	1.0	1.6	2.2	3.1
5.0	0.4	0.6	1.0	1.4	2.0
20.0	0.2	0.3	0.5	0.7	1.0
100.0	0.1	0.1	0.2	0.3	0.4

[a] Referred to in the text as "c." It is assumed that all samples of each group have about the same counting rate and are counted for about the same amount of time. A minimum of 10 counts must always be taken.

The Error of the Experimental Sample Corrected for Background. On the basis of the Gaussian distribution of error, the error of the sample corrected for background may be shown to be,

$$Q_y = \sqrt{Q_s^2 + Q_b^2} \qquad (8)$$

Since equation (5) applies to both sample and background,

$$Q_s = K\sqrt{N_s/t_s}$$

and

$$Q_b = K\sqrt{N_b/t_b}$$

Upon substituting these values of Q_s and Q_b into equation (8), and dividing both sides of the equation by the counting rate of the sample corrected for background, $(N_s - N_b)$, the fractional error of the sample corrected for background is obtained.

$$F_y = \frac{K}{N_s - N_b}\sqrt{N_s/t_s + N_b/t_b} \qquad (9)$$

Problem. A sample gave a counting rate of 200 cpm in a 10-minute count. The background gave a counting rate of 40 cpm in a 5-minute count. What is the fractional 0.9 error of the sample corrected for background?

Answer. A 0.9 error (confidence limit) corresponds to a K value of 1.65 (Table 2). Inserting the respective values into equation (9)

$$F_y = \frac{1.65}{200 - 40}\sqrt{200/10 + 40/5} = 0.055$$

There are 90 chances out of a hundred that the error of the sample corrected for background is less than 5.5%.

The easiest way of obtaining the error of any measurement corrected for background is probably by interpolation of a graph such as that given in Figure 1. This graph is prepared by use of equation (9) for a background characteristic of the instrument used for the measurement and the desired confidence limit. If the confidence limit used is the standard deviation as in Figure 1, the 0.95 error may be readily obtained by simply doubling the value for the standard deviation.

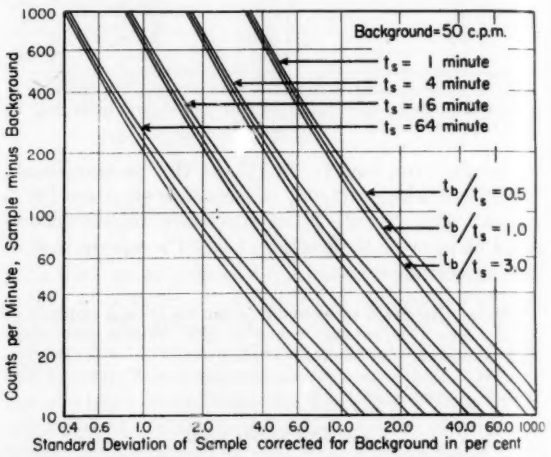

Figure 1. Statistical variations of measurements of radioactivity corrected for background.

The Counting Time Required for a Certain Statistical Error of the Count. In the determination of the amount of radioactivity it is usually desired to make the measurement to within a certain statistical accuracy. The total counting time required to reach this accuracy is the sum of the times devoted to the sample and to the background. It is dependent on the counting rates of the sample and the background and on the number of samples being counted. In order to most efficiently use counting time, the optimum ratio of counting time of sample to that of background, or an approximation of this ratio, should be employed.

In order to derive the relation which gives the amount of time required for the sample, t_b is made equal to ct_s, ct_s is substituted for t_b in equation (9), and the equation is squared and rearranged to give,

$$t_s = \frac{K^2}{F_y^2}\frac{N_s + N_b/c}{(N_s - N_b)^2} \qquad (10)$$

For optimum utilization of time, the ratio of time de-

voted to background to that devoted to sample, c, is obtained from Table 3, or it may be calculated according to equation (7). An approximation of the counting rate of the sample is usually available before the measurement is made, and the time to be devoted to measurement is usually determined on the basis of this approximation. The time required for the background is given by the equation,

$$t_b = ct_s \tag{11}$$

Problem. Four different samples, each counting about 100 cpm are corrected for the same background, which is about 50 cpm. For optimum utilization of counting time, how much time must be devoted to each sample and to the background, if the standard deviation of each measurement, corrected for background, is to be 5%?

Answer. By use of equation (7), the distribution of time between background and sample for optimum utilization, c, is found to be 1.4. Standard deviation means that $K = 1$ (0.68 error, Table 2). Upon inserting the proper values into equations (10) and (11),

$$t_s = \frac{1^2}{0.05^2}\frac{100 + 50/1.4}{(100 - 50)^2} = 22 \text{ minutes}$$

$$t_b = 1.4 \times 22 = 31 \text{ minutes}$$

The samples should each be counted for about 22 minutes, and the background for about 31 minutes.

When beginning a series of measurements, the most satisfactory way of obtaining an estimate of the required time is probably to approximate the optimum distribution of time between sample and background by reference to Table 3, and then obtain the amount of time required for measuring the sample to the desired accuracy by interpolation of a graph similar to Figure 1.

The Number of Counts Required for a Certain Statistical Error of the Count. When one uses a counter which records the time required to collect a designated number of counts, it is necessary to know how many counts, rather than how many minutes, are required to give the desired fractional error of the count. In order to obtain such an equation, both sides of equation (10) are multiplied by N_s, and the equation becomes,

$$n_s = \frac{K^2 N_s (N_s + N_b/c)}{F_y^2 \ (N_s - N_b)^2} \tag{12}$$

The number of counts required for a certain statistical accuracy as expressed in this equation is not dependent on the absolute values of the counting rates of the sample and background, but is dependent on the relation of these counting rates to each other. This may be demonstrated by expressing N_s in terms of a multiple of N_b, $N_s = kN_b$, and substituting this in place of N_s. In this way the equation is changed to,

$$n_s = \frac{K^2}{F_y^2}\frac{k(k + 1/c)}{(k - 1)^2} \tag{13}$$

Thus, for the same statistical error, as many counts must be taken of a sample having a counting rate of 20 cpm and a background of 10 cpm, as of a sample of 100 cpm and a background of 50 cpm. The sample of 20 cpm must be counted 5 times as long as the sample counting 100 cpm.

An equation for the number of counts required for the background is obtained by multiplying both sides of equation (11) by N_b, and by substituting n_s/N_s for t_s, and $1/k$ for N_b/N_s, to give

$$n_b = \frac{c\, n_s}{k} \tag{14}$$

Problem. A series of 5 different samples counting at about 100 cpm are corrected for a common background of about 40 cpm. How many counts must be taken of each sample and of the background in order that the 0.95 error of the determinations may be 5% and optimum use be made of counting time?

Answer. The proper values are inserted into equations (13) and (14)—a 0.95 error corresponds to a K value of 1.96 (Table 2); 5% corresponds to a fractional error of 0.05; the ratio of the counting rates of the samples to that of the background (k) is 100/40 = 2.5; by interpolation of the values given in Table 3, c is found to be about 1.5.

$$n_s = \frac{1.96^2}{0.05^2}\frac{2.5\ (2.5 + 1/1.5)}{(2.5 - 1)^2} = 5400$$

$$n_b = \frac{1.5 \times 5400}{2.5} = 3240$$

If one of the samples count at a rate less than 100 cpm, the error of that sample will be correspondingly larger.

If an automatic sample changer is used for counting, it is usually convenient to collect as many counts for the background as for the samples. In order to derive an expression for the number of counts to be collected for a certain statistical error, equation (11) is placed in the form,

$$c = n_b N_s / n_s N_b$$

When the number of counts collected for the background is equal to the number collected for each sample, $n_b = n_s$, and $c = N_s / N_b$, and by definition to k. By substituting k for c, equation (13) becomes,

$$n_{sb} = \frac{K^2\ (k^2 + 1)}{F_y^2 (k - 1)^2} \tag{15}$$

where n_{sb} is the number of counts collected for the background and also for the samples.

Choice of a Counting System. Two different counting systems are sometimes available to an experimenter, one of which has a higher efficiency than the other, but it usually also has a higher background. In a similar situation, the sensitivity of some instruments may be increased by increasing the operation voltage but this is accompanied by an increased background. The question arises in these cases as to which counting system, or which voltage setting, will give the most accurate count for a minimum of total counting time.

The total time required for counting is that of the samples plus that of the background, $t = mt_s + t_b$. When t_s and t_b are expressed in this equation in the terms given in equations (10) and (11) and $\sqrt{mN_b/N_s}$ is substituted for c, the following expression is obtained,

$$t = \frac{K^2}{F^2}\frac{(\sqrt{mN_s} + \sqrt{N_b})^2}{(N_s - N_b)^2} \tag{16}$$

The total time for the measurements as given in this equation assumes optimum distribution of time between background and samples. Since a comparison of the times required for different systems must be expressed on the basis of the same statistical error, the term K^2/F^2 may be assigned a value of 1, and the time required under this condition may be used as a basis for choice of a counting system, or voltage setting. The longer the time required the less desirable is the counting system. When only one sample is counted ($m = 1$), the reciprocal of the required time is equal to the "figure of merit" defined elsewhere by a somewhat different equation (*6*, *7*). When the conditions of counting are further limited by devoting equal counting

time to background and to sample, the relative merit of two different counting systems is expressed in terms of yet another equation (*8*).

Problem. Two different counting systems are available for measuring 2 different samples of about the same activity. With Counter *A* the samples corrected for background measure about 20 cpm, the background 25 cpm; with Counter *B* the samples corrected for background measure about 30 cpm, but the background is 50 cpm. Which counter gives the most accurate measurement for minimum time of counting?

Answer. Upon assigning K^2/F^2 a value of 1 and inserting the data for Counter *A* into equation (16),

$$t = \frac{(\sqrt{2 \times 45} + \sqrt{25})^2}{20^2} = 0.53$$

A similar calculation for Counter *B* gives 0.43. Counter *B* is preferred in spite of its higher background.

The Assessment of Counting Behavior

Sometimes during the process of counting, counts may be lost, or additional spurious counts may arise from electrical or mechanical interference, or some other causes. These sources of error usually contribute to non-statistical counter behavior and lead to undue irregularity in the rate of counting. Although this may usually be detected by simple observation of the interpolation lights, it is sometimes helpful to obtain an objective estimate of the extent to which the distribution of counts corresponds to a random distribution. This is conveniently done by use of the chi-square test.

In application of this chi-square test, a series of 10 or more measurements of the counting rate is made over identical intervals of time for each measurement and chi-square is calculated from the equation,

$$\chi^2 = \frac{(n_1 - r)^2 + (n_2 - r)^2 \ldots + (n_m - r)^2}{r} \qquad (17)$$

The value of chi-square is dependent on the number of times the count is measured and the deviation of each count from the average, but it is independent of the actual counting rate. A high value of chi-square, for any given number of observations, indicates a wide dispersion of observed values; a low value of chi-square indicates that values are close together. Intermediate values of chi-square may be expected from a series which has a true random distribution. As values become either higher or lower than a median value, the probability of obtaining these values in a true random distribution becomes smaller.

In order to determine the significance of the experimentally-determined value of chi-square, reference may be made to a table which gives for selected values of chi-square the probability that this or a higher value of chi-square would be obtained for a sample of truly random distribution. This table is available in many handbooks (*9*, *10*) and is published in a recent issue of THIS JOURNAL (*11*). The number of degrees of freedom recorded in this table is equal to one less than the number of determinations of the counting rate. If 20 determinations are made of the counting rate and the value of chi-square as calculated by equation (17) is 18.3, there is a probability of 0.5 (from the table), that is one chance in two, that the dispersion of values or a larger dispersion would have been obtained on the basis of statistical variation alone. Since the probability is also 0.5 that a smaller dispersion of values would have been obtained, the observed distribution obviously appears to be a true random distribution. Values of chi-square of 11.7 and 27.2 correspond to probabilities of 0.9 and 0.1, respectively, that greater dispersions would be expected on the basis of random distribution; values of chi-square lying between these limits are to be expected in 4 out of 5 determinations and therefore are indicative of random distribution. Values of chi-square less than 10.1 or greater than 30.1 would each be expected in 5% of measurements of a truly random sample. If values of about 10.1 or 30.1 are obtained experimentally it is indicated, in accordance with the usual rules of statistics, that the distribution is "probably" not a random distribution. Values of chi-square less than 7.6 and greater than 36.2 are each expected in only 1% of measurements. When these values are obtained it may be regarded as "quite certain" that the variation is due to sources other than a random distribution. Chi-square values for other than 20 determinations are available in the table; 20 is the recommended minimum number of observations necessary for an exhaustive analysis of counter behavior (*4*).

Problem. In twenty different measurements each over the same time interval, the following counts were recorded: 25, 20, 24, 31, 26, 24, 21, 19, 30, 33, 28, 31, 26, 21, 16, 20, 24, 26, 28, 27. Do these correspond to a random distribution?

Answer. Upon taking the mean of the above measurements and inserting the proper values into equation (17), chi-square is found to be 15.6. According to the interpretation given above, the counter is acting satisfactorily.

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Use of Radioisotopes in the College Chemistry Laboratory

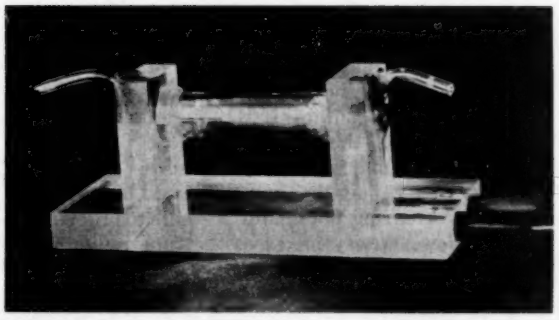
Everyday experience with radioactive isotopes in the high school and college chemistry courses is a goal toward which Dr. Willard Libby has challenged chemical education to strive. His reasoning behind this challenge is sound and is set forth in his Dallas address to the American Chemical Society (*1*).

The chief obstacles that have stood in the way of this goal are the extreme hazards associated with radioactivity and the high cost of isotopes and equipment. These have now been largely removed through the availability of "exempt quantities" of isotopes commercially at exceedingly low costs[1] and more significantly through the design of a cylindrical Geiger tube by Libby which facilitates radiochemical work with microcurie quantities of isotopes, quantities which the AEC has determined to be nonhazardous (*2*).

A report in THIS JOURNAL described radiochemistry instruction involving use of the "exempt quantities" of isotopes (*3*). Libby suggests in outline form several radiochemical procedures which can be used in conventional chemistry courses (*2*). The following communication adds to this list of experiments and relates some of the experiences the authors have had in using the cylindrical Geiger tube. The truly remarkable sensitivity of this tube (a meaningful count is obtainable from ordinary potassium salts in the laboratory) does, in truth, open up the possibility of "spiking" many of the reagents in a laboratory with isotopes at the microcurie level so that radiochemical techniques may supplant conventional techniques in many experiments. The consequence of this widespread use of isotopes is to: "increase general knowledge of the nuclear properties of matter. . .(and) to open for our whole society the potentialities of the Peaceful Atom" (*2*).

The Counter

The counter used in this project is of the thin-wall, continuous gas flow type (see figure). It is an outgrowth of the instrument developed at the Institute for Nuclear Studies in Chicago by Sugihara, Wolfgang, and Libby in 1952 (*4*). A Geiger counter very similar to this project's was used in the Chicago Sunshine Project (*5*). A clear sketch appears in reference (*2*).



Photograph of assembled cylindrical counter.

The counter has several advantages over standard, end-window Geiger tubes. It is able to count larger samples because the cylindrical "window" is uniformly sensitive over much of its area. This sensitivity factor also enables one to duplicate counting conditions with new samples with far less trouble than in the past.

For the educational institution there are several advantages. Delicate parts of the counter may be replaced for a few cents worth of material and a few hours labor. The gas supply is endless, which means the counter never wears out. Lastly, the structure is such that the student may view the working parts and thus gain insight into the actual principle of operation of Geiger counters.

While having the above advantages, the new counter has thin walls and can thus count soft beta particles as well as the standard Geiger tube.

Construction

The basic frame of the counter was machined of lucite plastic. The cost of material and labor was $25 for each of five frames. (The cost per instrument was high because of the labor time involved in following blueprint plans for the first counter.) The counter is used in conjunction with any satisfactory scaler which can supply a voltage of about 1000 v for operation in the Geiger range.

Absorption and Geometry Determination

Since a counter will not record every disintegration, it is necessary to find some method of interpreting counting data. This can be done with the use of the geometry factor, which is represented in the following equation as G (*5*).

This paper reports upon work performed by David Phillips as part of his Senior Honors research at the University of Redlands. The project was financed by the Atomic Energy Commission under the terms of contract AT(04-3)-173.

[1] Teachers and instructors not in immediate contact with isotope work might find help in a partial listing of some representative suppliers of these: Abbott Laboratories, Radioisotope Division, Oak Ridge, Tenn.; Atomic Research Laboratory, 10717 Venice Blvd., Los Angeles 34, Calif.; Tracerlab, Inc., 1601 Trapelo Road, Waltham 54, Mass.; Isotopes Specialties Co., Inc., 170 W. Providencia, Burbank, Calif.

As an example of the low cost of the isotopes available, the last named company supplies (without any AEC authorization being required) up to ten microcuries of any one isotope or combination of isotopes for $3.50 per microcurie. Carbon-14 is supplied as Na_2CO_3, cobalt-60 as $CoCl_2$ in HCl, sulfur-35 as H_2SO_4, etc.

$$G = \frac{A\sigma\lambda(1 - e^{-x}/\lambda)}{R}$$

where:

A = area of sample
σ = specific beta activity (disintegrations/mg/min)
λ = $x_{1/2}/\ln 2$
x = sample thickness (mg/cm²)
R = recorded counts/min (no absorber)

Geometry factor (G) turns out to be nothing more than the reciprocal of the percentage of particles the path of which carries them through the functional part of the counter.

Since A, x, and R can easily be determined, it remains only to find the half-thickness ($x_{1/2}$) of a sample for which σ is already known. Naturally occurring potassium, which contains 0.0119% radioactive potassium-40, fulfills all the requirements (*6*).

By taking counts with various absorber thicknesses, one may determine the half-thickness of a sample. Naturally occurring potassium presents a problem because its low activity increases the time requirements for accurate counting.

Measurements made for this project tended to agree with the aluminum half-thickness of 67 mg/cm² given by Martell (*5*).

For the counter used in this project, geometry was calculated using Martell's absorption value for potassium-40. Specific activity was determined as 89% of the total activity of the 0.119% potassium-40 found in naturally occurring samples of potassium salts. The half life used was 1.2×10^9 years (*6*). The computations gave a value for geometry factor of a 2.0-cm long sample of 2.30. That this is slightly smaller than Martell's value is accounted for by the fact that his counter is slightly shorter.

It was felt that the above geometry factor would be sufficiently close for all samples near 2.0 cm in length. The justification for this assumption is Martell's graph of geometry as a function of sample length (*5*). This plot indicates that the counter geometry is quite constant except for end effects.

Sample Preparation

Since sample thickness and area play an important part in counting, it is necessary that the technique of applying samples to sample holders allow a certain accuracy in determining these values.

For best results, it should be planned in advance to have a thickness near λ and a length not in excess of 2.0 cm. The sample should be placed midway between the ends of the holder in order to minimize deviations in geometry caused by end effects. The sample should be in the form of a powder or fine crystals to insure uniform thickness.

Samples should be weighed onto the holder from a weighing bottle. Addition of a few drops of alcohol to make a slurry will help in manipulating the sample into a rectangular area of uniform thickness and attach the sample to the holder. The alcohol will evaporate in a short time and thus bring about no change in sample thickness. The sample may be worked into the correct shape and thickness with the use of a small spatula and stirring rod. It is possible to keep an appreciable portion of the sample from sticking to these instruments. It was found that for the larger samples alcohol by itself was not enough to insure adherence to the bottom of the holder. In cases like this a mixture of collodian and ether was applied. A small layer of collodian served to keep crystals from breaking loose. At times it was found desirable to cover samples. In these cases a layer of Saran-Wrap was employed.

Radiochemical Qualitative Analyses

Experiments have been devised to make radiochemistry a natural part of the student laboratory experience. Thus, an experiment in qualitative analysis must be identified with the other course material, and all experiments should be at worst no more difficult than their classical counterparts.

Probably qualitative analysis offers the radiochemist fewer chances to practice his trade than almost any other branch of chemistry. However, it was felt that the freshman course should offer an introduction to radioactivity, since many students will not continue on in the study of chemistry.

Detection of Potassium

There are only six naturally occurring beta emitters below lead on the periodic table. These include potassium, rubidium, rhenium, lanthanum, neodymium, and lutetium (*7*). Of these, only potassium is ordinarily used in freshman qualitative analysis. Because it is unique among the elements as the only radioactive one, potassium may be tested for directly by the simple expedient of finding out whether or not the unknown is radioactive.

Since counter efficiency for potassium-40 appears to be about 25%, and since the specific beta activity for KCl is 0.919 dis/mg/min it can be expected that 25 mg mixed in with other unknowns would yield about ten counts per minute. This should be a sufficient increase over background to insure the presence of radioactivity in the sample within a few minutes.

It is suggested that the student either use part of the original dry sample or that an adequate volume of dissolved sample be evaporated to dryness. In either case the sample may be mounted by the usual method, but it does not have to be weighed.

It is felt that this experiment will be of twofold use, first of all because it overcomes difficulties students have in flame detection of potassium (especially in the presence of sodium) and is easier than the chemical test, and secondly because it introduces the student to the fact that naturally occurring radioactivity is really a very normal part of our common environment.

Confirmatory Magnesium Test Using P^{32}

The very chemical similarities that allow classification of elements in groups become deterrents to use of tracers in qualitative work. However, magnesium is in a group by itself, acting almost, but not quite, like the heavier alkaline earths. Because it is more soluble than certain compounds of calcium, strontium, and barium it may be separated completely from these elements.

In the procedure suggested here, as complete removal as possible of calcium, strontium, and barium is achieved through the addition of excess carbonate, oxalate, and sulfate. Di-sodium ammonium phosphate tagged with radioactive phosphorus-32 is then added,

the ratio being about five drops of phosphate to two drops of unknown. The precipitate is then mounted and counted. (This is calculated for similar molarities of magnesium and ammonium phosphate ions.) If the count represents a fairly good percentage of the tracer added (20%), the student should expect a positive blue lake test. If the activity is very low, the precipitate probably represents only Group IV traces.

Isotope Dilution

One of the radiochemical techniques with the most potential in college chemistry is the isotope dilution method of quantitative analysis. Many elements for which there is no complete precipitation and no good titration reaction can be simply determined by this method. In addition, the old and tedious gravimetric experiments can be simplified to a considerable degree.

The essential procedure is as follows: A solution contains an unknown quantity of an ion which is to be determined quantitatively. To the solution is added an isotope tracer of the ion to be analyzed. The tracer activity must be known. Chemically speaking, the addition of the tracer will make almost an infinitesimal alteration in ion strength. After the tagged solution has been mixed, a precipitating agent is added. Then a portion of the precipitate is weighed, counted, and its activity computed. This activity represents a certain fraction of the original activity. It follows that the ion fraction in the sample will be the same, since the solution with the tracer was homogeneous. Thus, it is possible to use precipitates which have a solubility appreciable enough to rule them out of classical gravimetric experiments, and it is not necessary to go through the tedious weighings and reweighings that characterize the older analytical method.

Chloride Determination

Silver chloride is insoluble and can be analyzed by using constant weight filtering crucibles. However, isotope dilution offers a more efficient method, and even suggests the possibility of substituting partial precipitation of a water soluble chloride salt through the addition of alcohol to the unknown solution.

In many ways chlorine-36 is superior to sulfur-35 as a radioisotope. Its half life is 4.4×10^5 years as compared to 87.1 days, and its maximum beta energy is almost five times as great as that of sulfur-35, which means it is much less easily absorbed.

Absorption data were taken for chlorine, with the results indicating an aluminum half-thickness of 30 mg/cm^2.

Sodium chloride samples were tagged, precipitated out as silver chloride, counted, and compared for agreement. The error was 1%, which is the statistical limit of counting accuracy.

For the best results it is suggested that chloride counting sample be in the neighborhood of 200 mg mass with counter activity in the neighborhood of 1000 counts/min.

Exchange Between Sulfite and Thiosulfate

Probably the most exciting aspect of radiochemistry is the chance to probe into studies never before possible, particularly in the area of reaction mechanisms, exchange reactions, and molecular rearrangement. The radiochemist can distinguish between two chemically identical atoms to make this possible.

A good example of exchange mechanism is the sulfite-thiosulfate pair. Chemically, it is obvious that the two are closely related since one method of synthesizing thiosulfate is to heat a solution of free sulfur and sulfite in an alkaline medium. Furthermore, it is easy to separate thiosulfate into sulfite and free sulfur, and many thiosulfates are unstable at room temperature and decompose into those two units quite rapidly (*8*).

The experiment revolves around the fact that when tagged sulfite and normal thiosulfate are heated together some of the radioactivity will gradually appear in the thiosulfate ion (*9*).

The first step necessary is the preparation of tagged sulfite. This may be accomplished by adding sulfate tracer to the desired quantity of normal sulfate. It it best to keep quantities small because of the weak maximum energy of the beta from sulfur-35. The sulfate should be heavily acidified and reacted with copper, the resulting sulfur dioxide being collected in sodium hydroxide.

The thiosulfate should be added to the basic sulfite solution. The new solution should be heated to 80 or 90° C for 15 minutes to an hour. At the end of this time sulfite may be removed as strontium sulfite precipitate. If barium ion is then added in sufficient concentration, a certain amount of the thiosulfate may be precipitated for counting. There should be a detectable amount of radioactivity.

An interesting sidelight to the experiment is the reaction: $2Ag^+ + S_2O_3^= \rightarrow Ag_2S + H_2SO_4$. By this means it may be determined whether the radioactivity is common to both sulfurs or only one. The correct answer is, of course, that only the "center" sulfur will have activity.

These two interesting conclusions can be drawn from the experiment. First, there is interchangeability between the two ions, and second, the "outside" sulfur has nothing to do with the exchange itself, and is less like its companion sulfur than is the sulfite ion.

Chemical Kinetics

A satisfactory experiment on chemical kinetics utilizing microcurie amounts of radioisotopes and the special cylindrical counter is the measurement of the rate of exchange of I^- ion with an organic iodide. The exchange of ethyl and propyl iodide with I^- in alcoholic solution has been found to follow second order kinetics (*10*). Iodine-131 (8 day half life) is available as sodium or potassium iodide in the microcurie amount. The alkyl iodide, separated at time intervals from the solution in which exchange is taking place, is transferred to a piece of filter paper mounted on the inside of the lower split cylinder of Bakelite. Scotch tape is quickly spread over the paper to seal in the volatile liquid.

Additional experiments which are readily performed with this counter using available low level isotopes are under study and will be reported from time to time. Instructors are urged to make their own adaptations of laboratory experiments and to share these through the pages of THIS JOURNAL. Organic chemistry instructors will find the recent book, "Tracer Applications for the Study of Organic Reactions," by John G. Burr, Jr., Interscience Publishers, N. Y., of special interest.

Acknowledgment

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Separation of Ce^{144} from Pr^{144}

A radiochemistry demonstration

This paper describes an instructive radiochemical experiment that can be carried out by students with equipment available in many high school laboratories. It involves the separation of two radioisotopes by a basic chemical procedure: filtration of an insoluble precipitate. Besides being an exercise in careful technique, this demonstration introduces the students to such fundamental concepts of nuclear chemistry as half life, the mother-daughter relationship, and the use of carriers. It also illustrates two practical uses of oxidation-reduction reactions, and calls attention to an otherwise little-mentioned part of the periodic table, the rare earths.

Cerium (58) and praseodymium (59) are the first two members of the series of 14 consecutive elements (58–71) known as the rare earths. These metals all have a normal oxidation state of +3, and in almost every other respect their chemical properties are identical, but this demonstration takes advantage of one of the rare exceptions: the property of cerium to exist in the valence state +4 and form an insoluble iodate. The standard method of isolating cerium from the other rare earths is by filtering this precipitate.[1] In this case, the filtration can be used to separate the radioisotope cerium-144 from its daughter praseodymium-144.

Cerium-144 is one of the most prominent fission products. It has a half life of 285 days, decaying by beta-emission into an isotope of the next highest element, praseodymium-144. The latter (or "daughter" isotope) has a half life of only 17 minutes, and is normally found in equilibrium with its "parent." The chemical shorthand for the pair is $Ce(Pr)^{144}$, which implies an average of one disintegration of Pr^{144} for each nuclear event in which it is formed; that is, for each disintegration of Ce^{144}.

The quantity of radioactivity necessary to carry out this experiment is that which gives a significant reading on a "Classmaster" Geiger counter, and is of the order of 1 microcurie, or 2.2×10^6 decompositions/minute (of *each* of Ce^{144} and Pr^{144}). The regulations of the United States Atomic Energy Commission permit the unlicensed possession and use of 1 microcurie of $Ce(Pr)^{144}$.[2] This may be purchased from Oak Ridge for a small handling charge, but it is recommended that the instructor first solicit a contribution from the nearest nuclear laboratory.

The mass of 1 microcurie of Ce^{144} is about 3×10^{-4} microgram, and of Pr^{144}, about 10^{-3} microgram. Relatively gross quantities of inert isotopes of each element must be added to exceed the solubility product of ceric iodate and "hold back" the trace of daughter from being physically trapped in this precipitate. Ceric ammonium sulfate is a common laboratory reagent. Other more readily available rare earths, such as neodymium, or even crude rare earth mixtures, may be used as the praseodymium carrier.

Once the Pr^{144} has been isolated from its parent, its decay can be followed by noting the Geiger counter readings as a function of time. These observations can be started at any arbitrary time, but it is recommended that the first measurement be taken as soon as the filtration is complete. Less than 10% of the radioisotope will remain after an hour, at which time the background will probably have become a significant fraction of the Classmaster counting rate.

[1] CORYELL, C. D., AND SUGARMAN, N., "Radiochemical Studies: The Fission Products," McGraw-Hill Book Co., Inc., New York, 1951, Book 3, pp. 1668, 1692.

[2] The Federal Register, Title 10 (Atomic Energy), Chapter I (Atomic Energy Commission), Part 30 (Licensing of Byproduct Material) No. 30.21*a*.

Meanwhile, the daughter will be building up again in the depleted Ce^{144} precipitate. In an hour, more than 90% of the equilibrium concentration of Pr^{144} will be reached and the mixture will be suitable for repeating the experiment. Thus it is possible to have one of the separated isotopes disintegrate to zero counting rate for one class and yet have it back again at the original strength for the beginning of the next. It may be added that there is no practical way to bring a short-lived isotope into the high school laboratory other than by milking the daughter from a couple such as $Ce(Pr)^{144}$, $Ce(Ba)^{137}$, or $Sr(Y)^{90}$, and of all available mother-daughter pairs, none is safer or more convenient to use than $Ce(Pr)^{144}$.

A preliminary version of the procedure presented below was used to instruct students at Westbury High School, Westbury, Long Island, in preparation for their performance of it as a demonstration-exhibit at the Mid-Island Science Fair, April 24–26, 1958. During the three days of the Fair, which was held at the Westbury School, the demonstration was carried out about 20 times, with nine students participating. The procedure was improved considerably during this time, largely due to the interest and imagination of one of the students, who is co-author of this paper. He also did a considerable amount of later work on the experiment and is largely responsible for the clarity of the procedure and notes. Incidentally, the amount of supervision required near the end of the Fair had decreased to nothing as the young scientists gained confidence in their abilities to perform and explain the experiment to other students. On the last day, completely on their own, they carried out five consecutive separations with the same one-microcurie batch of activity and succeeded in demonstrating the 17 minute half life of Pr^{144} each time.

The Experiment

In this demonstration, milligram quantities of cerium and praseodymium are separated by filtration of the insoluble iodate salt of cerium in the oxidation state +4. The chemical steps involved are outlined in the equations below and in the figure. The normal oxidation state for rare earths is +3, and praseodymium cannot be oxidized to the +4 state, nor is $Pr(IO_3)_3$ insoluble. A trace of the radioisotope Ce^{144}, in equilibrium with its daughter Pr^{144}, provides a convenient means of following the progress of the separation. The presence of Pr^{144} can be identified in the filtrate by following its decay with a Geiger counter, since it has a half life of only 17 minutes. The $Ce(IO_3)_4$, including the Ce^{144}, may be decomposed with H_2O_2 and used again in an hour, after which time the Pr^{144} daughter will have again built up to near-equilibrium concentration.

Equations

$$6H^+ + BrO_3^- + 6Ce^{+3} \rightarrow Br^- + 6Ce^{+4} + 3H_2O$$

$$Ce^{+4} + 4IO_3^- \rightarrow Ce(IO_3)_4$$

$$2Ce^{+4}\ [\text{in } Ce(IO_3)_4] + H_2O_2 \rightarrow Ce^{+3} + 2H^+ + 3O_2$$

Procedure

(1) Dissolve 17 mg of ceric ammonium sulfate in 5 ml of 5 *N* HNO_3 in a 150-ml beaker. Label the beaker *A*. Add one microcurie of the radioactive tracer $Ce(Pr)^{144}$ in solution, and 1 ml of a solution of $PrCl_3$ containing 9 mg/ml. Other rare earths besides cerium may be substituted for praseodymium with equal success. Add 1 ml of a 1 *N* $NaBrO_3$ solution to beaker *A* and warm the mixture on a hot plate or steam bath for about 5 minutes (to 50–70°).

The quantities are equivalent to 5 mg each of cerium and praseodymium (neodymium and samarium were substituted for the latter in the authors' laboratories). The anions do not take part in the chemical reactions, and the same results would be obtained with other soluble compounds of these rare earth elements. In the reagent specified, cerium is in the +4 oxidation state, but when the activity is recycled it will be in the +3 state. Warming the mixture increases the oxidation rate, and helps prevent Ce^{+3} from passing into the filtrate during the separation of $Ce(IO_3)_4$, which would carry Ce^{144} into the Pr^{144} fraction and spoil the decay measurement. It is recommended that the experimenter wear surgeons' gloves to prevent contamination of his hands in the event of a spill. All work is done over trays lined with paper towels, and a radiation warning sign is displayed.

(2) Pour the contents of beaker *A* into a 15-ml test tube and cool in an ice bath for 2–3 minutes. Then add 4 ml of a saturated solution of $NaIO_3$. A thick yellow precipitate of $Ce(IO_3)_4$ should begin to form immediately. Leave the test tube in the ice bath an additional 3 minutes.

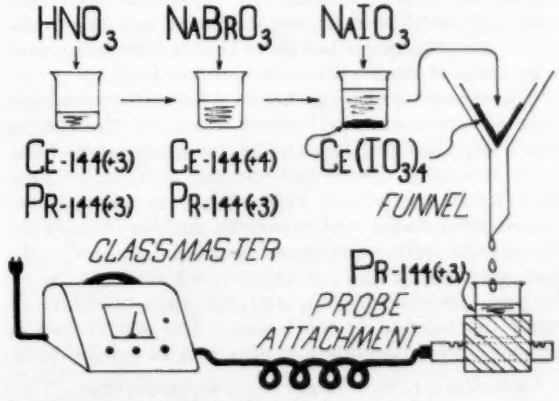
Cooling the mixture before adding the $NaIO_3$ prevents the latter from being decomposed by hot HNO_3, and further cooling insures the complete precipitation of the $Ce(IO_3)_4$. The great excess of $NaIO_3$ also helps to make the precipitation of Ce^{+4} quantitative.

(3) Transfer the contents of the test tube onto a fluted filter paper, and collect the filtrate, which should be absolutely clear, in a 150-ml beaker labeled *B*. Wash the precipitate twice with 1–2 ml of water.

The filtrate may be slightly yellow rather than water-white, but any turbidity is an indication that some precipitate has passed through, and the filtration should be repeated. It is convenient to keep the volume of liquid in beaker *B* to a minimum.

(4) Place beaker *B* in the special container housing the Geiger counter probe, and measure and record the radiation level. Continue to record the readings and times at approximately 3-minute intervals for at least one-half hour.

The probe-beaker support attachment maintains a 150-ml beaker in a stationary position in close proximity to the probe (see figure). The actual dimensions are not critical, since only



Flow sheet of radiochemical separation.

relative counting data are used. The background radiation level must be subtracted from that indicated on the ratemeter before plotting to determine the half life of the filtrate activity. Since radioactive decay is exponential, a straight line should be obtained if the data are plotted on semilog paper. If the radiation level decreases by one-half every 17 minutes, the experiment is successful. If not, some of the Ce^{144} has passed through the filter paper into the filtrate. This remains as residual activity in beaker *B*, indicating an incomplete separation. In all probability, some point in the procedure was overlooked or carelessly performed. One microcurie gives a satisfactory counting rate on the Classmaster laboratory monitor (available from Nuclear-Chicago Corp., Chicago, Ill.). If another instrument is used, add enough radioactive tracer to measure at least two-thirds of full scale on the ratemeter. Inquiries about purchases of $Ce(Pr)^{144}$ may be directed to the Radioisotopes Sales Dept., Oak Ridge National Laboratory, Oak Ridge, Tenn. Applications for a Byproduct Materials License (required for possession of more than one microcurie) are submitted to the Division of Licensing and Regulation, U. S. Atomic Energy Commission, 1717 H Street, Washington 25, D. C.

(5) The cerium and Ce^{144} caught as a precipitate on the filter paper is now reclaimed, as follows: Place beaker *A* under the funnel, and add slowly to the precipitate 10 ml of a 3% solution of H_2O_2, followed by 5 ml of 5 *N* HNO_3. Stir cautiously, and, after the funnel drains, repeat the washing procedure. Evaporate the contents of beaker *A* on a hot plate or steam bath, preferably in a hood. When dry, it may be redissolved in 5 *N* HNO_3, and recycled, starting again at Step 1 (except that cerium carrier need not be added).

Traces of iodine in the dry residue (purple color) may be removed by adding 1–2 ml of water and evaporating again. Between experiments, beaker *A* should be labeled "Radioactive Material, $Ce(Pr)^{144}$, one microcurie." It is convenient to use masking tape bearing the conventional symbol of radioactivity. One hour should pass between separations to permit Pr^{144} to build up in beaker *A* and approach equilibrium with the Ce^{144}.

(6) All apparatus that has come in contact with contaminated material is now thoroughly washed. The contents of beaker *B* are disposed of by carefully pouring down the drain of a sink and thoroughly flushing with water. The filter paper and paper towels used to line trays are carefully collected, wrapped in additional paper, sealed with masking tape, and thrown out as "radioactive waste." This concludes the experiment.

The surgeon's gloves are washed with abrasive soap (e.g., "Ajax") and water before removal. The possible contamination levels from this experiment represent no health hazard, but good housekeeping is stressed throughout as a fundamental part of the radiochemical technique.

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Construction of Molecular Models

In the continuing search for more perfect molecular models, commercial sets have become ever more elaborate and costly. The set described in this communication compares favorably in utility with many of the more expensive models, yet it can be constructed cheaply and without the aid of elaborate technical resources which are available only under special circumstances.[1] Models of greater simplicity and lower cost have been described,[2] but these lack the flexibility and ruggedness of the models to be described here.

The atoms comprising this model are sponge rubber balls of various sizes and colors, which are available in retail stores at small cost. The bonds are made from $^3/_8$-inch wooden dowels and pieces of a $^3/_8$-inch screen door retaining spring. The other raw materials required are a strong rubber cement, such as "Pliobond" (Goodyear), rubber tubing of $^5/_{16}$-inch i.d., $^1/_2$-inch o.d., and plaster of Paris. A plaster cast serves as a jig to hold the rubber balls, and also as a template to mark the location of the bonds. The plaster cast is prepared by immersing a rubber ball to a little more than half its diameter into the freshly mixed plaster investment, and allowing the latter to set; e.g., a $2^1/_4$-inch ball is immersed to a depth of $1^1/_2$ inches.

When the plaster is set, the rubber ball can be removed easily from the cast. Owing to the fact that the cast encloses somewhat more than one-half of the sphere, the rubber balls are held tightly, and they may be inserted and removed from the cast as often as desired for the purpose of marking and subsequent drilling of the holes. For carbon atom models the positions of the tetrahedral angles are marked on the cast by placing a cardboard equilateral triangle in the spherical hollow of the cast in an approximately horizontal position and marking the points where the apices of the triangle touch the wall.[3] The cast is clamped by its top and bottom surfaces into an adjustable drill press vise, and it is aligned for drilling by placing a drop of mercury (or a small bead) in the hollow and adjusting the position of the cast so that the mercury (or bead) comes to rest on one of the three marks. This alignment

[1] Subluskey, L. A., J. Chem. Educ., **35**, 26–29 (1958).
[2] Tanaka, J., J. Chem. Educ., **34**, 603 (1957).

[3] The length of the side of the triangle is given by the expression $l = 0.817 \times d$, where l = length of side of triangle and d = diameter of rubber sphere.

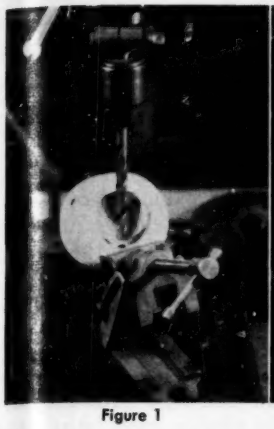

Figure 1

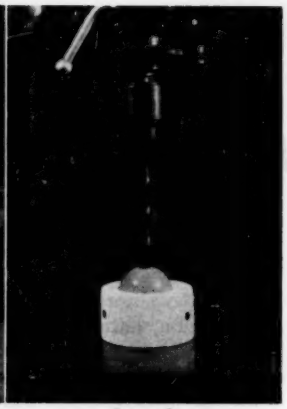

Figure 2

Figure 1. Drilling tetrahedrally spaced holes in plaster cast.
Figure 2. Mounting ball in cast for drilling.

is necessary to ensure the accurate placement of the marks on the rubber spheres subsequently. A hole is then drilled vertically through the cast at the mark. A drill bit with an extended shaft may have to be used to permit the chuck to clear the cast (Fig. 1). Two holes are drilled at the other two marks in the same manner.

Locating Tetrahedral Bonds

The finished plaster jig is now used to make atom models with tetrahedral bonds. A rubber ball is inserted into the jig and marked at the sites of the three holes by means of a refill unit from a ball point pen. The fourth mark is placed on the ball by readjusting its position in the cast so that two marks coincide with two holes and the third mark comes to lie at the upper pole of the ball. The exact equidistant positioning of the four marks on the ball should be checked with a compass. Only a small correction should be required, if any. The ball is reinserted into the cast so that one of the marks comes to lie exactly at the top. This can be checked by observing the mark at eye level while rotating the cast and sphere on a level surface and by observing whether the mark describes a point locus. If the mark is off-center, it will describe a circle instead. When a satisfactory adjustment has been made, a hole is drilled at the mark down to the center of the sphere (Fig. 2), e.g., for a $2^1/_4$-inch sphere down to a depth of $1^1/_8$ inches. A $^7/_{16}$-inch drill bit is used at the highest speed obtainable. Occasionally a piece of sponge rubber is not disintegrated by the bit and this causes vibration of the ball and cast. Such a piece should be torn off so that the drilling will continue smoothly. Three more holes are drilled at the other marks in the same manner. Finally, pieces of rubber tubing cut to a length $^1/_4$-inch less than the radius of the sphere, are cemented into the holes in order to protect the sponge rubber from excessive wear.

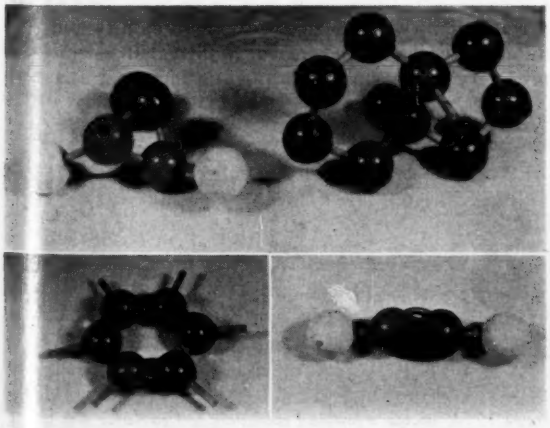

Figure 3. Typical models showing variety of structural representations. *Top left:* cyclopropane derivative; *top right:* a *trans*-fused perhydro indene; *lower left:* benzene; *lower right:* acetylene.

The elements from carbon to fluorine are represented by spheres of different colors, but of the same size, permitting one jig to be used to make models of all these atoms. Models of nitrogen are constructed in exactly the same manner as the carbon models. Normally only three of the four valences will be used; in models representing quaternary nitrogen or nitro groups all four valences will be required. The same plaster cast is used also as the jig for the oxygen model, but holes are drilled at only two of the four marks. The tetrahedral angle (109°28′) can be used as the valence angle at the oxygen atom, since the C—O—C bond angle in dimethyl ether is 111°. If oxonium compounds are to be depicted, a third hole is added midway between the other two marks on the sphere. For the elements from silicon to chlorine, spheres of a larger size and a larger jig are used than for the elements of the first period. Bromine and iodine require still larger spheres and jigs. All these jigs are equipped with holes to give tetrahedral bond angles and provide for the representation of the univalent halogens, of phosphates, sulfates, and of the halogen oxyacids. Since the bond angles in derivatives of divalent sulfur, trivalent phosphorus, and other elements of the second and higher periods differ substantially from the tetrahedral angle, separate sets of holes have to be added to the jigs in order to make models of such atoms. Hydrogen atoms are represented by smaller spheres than carbon. They need not be made of an elastic material. If a hole is drilled through the sphere along its diameter, only one end of the resulting channel is used for a singly bonded hydrogen atom. A hydrogen bond may be depicted by inserting dowels at both ends of the channel.

If the balls representing the carbon atoms are $2^1/_4$ inches in diameter, the relative lengths of single, double, and triple bonds are reproduced most faithfully by wooden dowels $2^1/_2$ inches long, springs $2^1/_2$ inches long, and springs $3^1/_2$ inches long, respectively. For ease of insertion the dowels and springs are lubricated with glycerol.

The models described have an advantage over most others insofar as only one type of carbon atom is required for the construction of all kinds of strained molecules, including three member rings, and the same carbon models serve, in conjunction with springs, to depict double and triple bonds and aromatic structures. Yet the resulting models are sufficiently rigid to maintain the distinction between "boat" and "chair" forms of cyclohexane rings, and models of complex organic molecules such as polypeptides, steroids, and porphyrins can be constructed readily.

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Accurate Molecular Models

Since the beginning of the modern era of chemistry, chemists have speculated upon the actual appearance of atoms, ions, and molecules. Because most molecules are too small to be seen even with the electron microscope, scientists have resorted to making models which have agreed as nearly as possible with available data on atomic and molecular dimensions. As early as 1881 a United States patent was issued for a primitive system of atomic models (*1*). More recent representatives include the inexpensive but purely schematic ball-and-peg models, the Fisher-Hershfelder-Taylor models, and various modifications of the Stuart-Briegleb (LaPine) models. All but the ball-and-peg models possess the serious drawbacks of high price, inflexibility, and inability to construct many well-known but rather strained molecules. Thus it has been impossible to model cyclopropane derivatives, while cyclobutanes, bicyclic systems, and unsaturated fused 5, 6-membered ring systems could be modeled only by the use of specially modified atoms or bonds of unrealistic length.

The inception of the present set of molecular models was based upon a long-felt need for models which would (1) represent as accurately as possible all of the physical characteristics of real molecules, and (2) be available at a price which would permit their use by the average student of chemistry. These aims have been accomplished by taking advantage of the methods and materials made available by our modern plastics industry.[2]

Principles of Construction

A serious shortcoming of previous models which faithfully reproduce known covalent bond lengths has been the use of flattened surfaces normal to the covalent bonds of both multivalent and univalent atoms. This has led to an unrealistic degree of immobility in the resulting completed models of molecules. For example, most models of cyclohexane are interconvertible from boat to chair configurations only with difficulty, often at the expense of bond rupture. The usual models of optically active biphenyls such as O,O′-dichlorodiphenic acid suggest that they should not be capable of racemization, although it is found experimentally that this substance may be racemized (*2*), but that O,O′-dinitrodiphenic acid may not (*3*). These problems of inflexibility have been surmounted by providing all atoms having covalences in two or more directions (C, O, N, S, and P) with rounded bonding surfaces which allow the atoms to rock realistically with respect to each other. It is immediately possible to interconvert boat and chair forms of cyclohexane (see Fig. 3), and to demonstrate correctly that O,O′-difluoro- and dichlorodiphenic acids racemize with increasing difficulty while it is impossible to racemize the model of O,O′-dinitrodiphenic acid without bond rupture.

The non-sigma-bonding electrons (usually *p*- or π-electrons) of atoms occupy orbitals which are not directed toward bonded atoms and which give rise to the observed van der Waals radii. These orbitals are compressible when crowded by neighboring atoms to a degree which is roughly dependent upon atomic radius. Thus chlorine and sulfur should be more compressible than carbon nitrogen. This feature is qualitatively built into the present models by hollow-molding in resilient plastic which "gives" to an increasing degree as the van der Waals radius increases. An extremely important advantage of this flexibility is the ability to construct, without special atoms or unrealistic bonds, *all* strained systems, including the smallest known cycles. Nevertheless, sterically impossible structures cannot in general be modeled for the same reasons which prevent their existence in actual molecules. A further consequence is that whereas in the past it has been necessary to employ as many as eight different representations of carbon atoms to suit all structural variations, the flexibility of this set allows all structures to be built with only the types of carbon atoms which actually exist. Similarly, only the different basic shapes of all multivalent atoms are necessary for accurate representations, and the con-

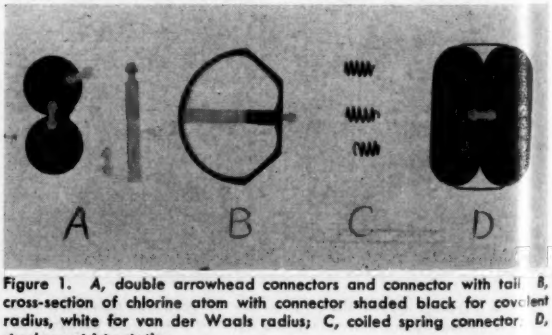

Figure 1. *A*, double arrowhead connectors and connector with tail. *B*, cross-section of chlorine atom with connector shaded black for covalent radius, white for van der Waals radius; *C*, coiled spring connector. *D*, staples restrict rotation.

[1] Present address: 107 Jamesville Road, DeWitt, New York.

[2] The models described herein are available at a price of about fifty cents per atom from the Bronwill Scientific Division of the Will Corporation, Rochester 10, New York, as well as a number of other laboratory supply houses throughout the United States and Canada. The standard set of 100 atoms consists of 17 tetrahedral carbon, 15 trigonal carbon, 5 digonal carbon, 32 hydrogen, 5 digonal oxygen, 5 carbonyl oxygen, 5 quaternary nitrogen, 5 nitrogen amine cap, 5 trigonal nitrogen, 4 chlorine, and 2 digonal sulfur. Additional types of atoms will become available in the future.

fusing multiplicity of models for the same atom is avoided.

A major consideration has been the design of connectors which hold the atoms together. It is necessary to have connectors large enough for easy handling, which may be easily inserted into receiving holes in the atoms, and which form bonds resistant to rupture by both straight and angular tension. The connectors are illustrated in Figure 1*A* and *B*. This design permits facile insertion of the connectors, either by twisting them or by squeezing the atom to elongate the receiving hole. A strong bond is produced because the base of the arrowhead is much broader than the diameter of the entrance hole. Connectors for atoms which have valence in only one direction (H, Cl, carbonyl O) are semi-permanently inserted and are equipped with tails which extend to the rounded inner surface of the atom; see Figure 1*B*. Such atoms are readily connected to others by squeezing the atom to grasp the tail, or by pushing against the end of the tail.

In order to provide the bond strength necessary to hold together chains of more than about thirty members, short coiled springs (Fig. 1*C*) are supplied.[2] Atoms are joined by screwing them together along the spring, and the bond strength thereby achieved is sufficient to permit construction of straight chains of several hundred members, which will support all attached groups.

Restricted rotation about multiple bonds is accomplished, as shown in Figure 1*D*, by inserting the special wire staples which are supplied with the set into the ends of adjacent capsule-shaped atoms such as trigonal carbon and nitrogen. This method of representing restricted rotation has the advantage that although free rotation is prevented, the atoms may twist along the axis joining them to the extent of about 40°, which gives a realistic picture of this property of double bonds.

The table records the dimensions of atoms used in the design of this set. Most of the values are taken from microwave spectroscopic measurements which yield exceptionally accurate data. Use has also been made of the best electron- and X-ray-diffraction data as well as Raman and infrared spectra. For covalent radii, the well-established single-bond radius of carbon was subtracted from all interatomic distances reported for other atoms singly bound to tetracovalent carbon. Thus the single bond radii listed in the table are the most universally useful lengths derived in this manner

[2] This method of bonding was suggested by Dr. Kotaru Murai of the Charles Pfizer Laboratories, Brooklyn, New York.

Atomic and Molecular Model Dimensions. The Second Figure in Italics is the Model Size in Inches.
Scale: 1.00 inch = 1.54 Å.

Atom	Radii: Covalent	Radii: van der Waals	Bond angle
C-tetrahedral	0.77° Å[a]	...	109° 28′[b]
	0.500	...	
C-trigonal	0.695 Å[c]	1.80 Å[d]	120°[e]
	0.451	*1.17*	
C-digonal	0.605 Å[f]	1.80 Å[g]	180°[h]
	0.393	*1.17*	
H	0.30 Å[i]	1.00 Å[j]	...
	0.195	*0.650*	
N-tetrahedral	0.70 Å[k]	...	109° 28′[l]
	0.455	...	
N-amine cap	(0.70 Å)	1.50 A[m]	...
	(*0.455*)	*0.974*	
N-trigonal	0.65 A[n]	1.60 Å[o]	120°[p]
	0.422	*1.04*	
N-nitrile	0.55 Å[q]	1.50 Å[r]	...
	0.358	*0.974*	
O-digonal	0.66 Å[s]	1.40 Å[o]	105°[t]
	0.429	*0.908*	
O-carbonyl	0.51 A[u]	1.60 Å[o]	...
	0.331	*1.04*	
O-trigonal	0.65 Å[v]	1.60 A[o]	120°[w]
	0.422	*1.04*	
S-digonal	1.04 Å[x]	1.70 A[o]	104°[y]
	0.675	*1.10*	
S-thionyl	0.94 Å[z]	1.85 A[aa]	...
	0.610	*1.20*	
S-tetrahedral	0.99 Å[bb]	...	109° 28′[bb]
	0.643	...	
F	0.60 A[cc]	1.35 Å[o]	...
	0.390	*0.876*	
Cl	0.99 Å[dd]	1.80 Å[ee]	...
	0.643	*1.17*	
Br	1.14 Å[ff]	1.95 Å[o]	...
	0.740	*1.27*	
I	1.36 Å[gg]	2.05 Å[o]	...
	0.883	*1.33*	
P-pentavalent	1.05 Å[hh(13)]	...	102°[hh(14)]
	0.682	...	
P-trivalent cap.	(1.05 Å)	1.85[ee]	...
	(*0.682*)	...	
B-trigonal	0.80 Å[ii]	...	120°[ii]
	0.520	...	
Si-tetrahedral	1.07 Å[jj]	...	109° 28′[jj]
	0.695	...	
Metal 1[kk]	1.23 Å[mm]	...	90°
	0.798		
Metal 2[ll]	1.33 Å[nn]	...	90°
	0.864		
Metal 3[mm]	1.42 Å[nn]	...	90°
	0.922		

[a] (10) p. 161. [b] (10) p. 84; (11) p. 172. [c] (10); (11) p. 172. [d] (10) p. 189; (11) p. 98. [e] (11) p. 172. [f] (7) pp. 371–2; (8) p. 452; (11) p. 162. [g] (11) p. 100. [h] (11) p. 172. [i] (7) p. 317; (11) p. 168. [j] (11) pp. 99 and 103. [k] (8) pp. 450–1; (9) p. 276. [l] (8) p. 450; (10) p. 80; (11) p. 173. [m] (10) p. 189; (11) p. 99. [n] (8) pp. 452–3. [o] (11) p. 99. [p] (10) pp. 200 and 209; (11) p. 173. [q] (7) p. 371; (8) p. 452; (10) p. 164; (11) p. 163. [r] (10) p. 189. [s] (7) p. 373; (8) p. 450; (9) p. 273; (11) p. 160. [t] (7) p. 372; (8) p. 450; (10) p. 79; (11) pp. 157 and 174. [u] (7) p. 373; (8) p. 451; (9) pp. 271 and 276. [v] (9) p. 306; (12). [w] (12). [x] (9) p. 275; (11) p. 162. [y] (10) p. 79; (11) p. 174. [z] (10) p. 164. [aa] (10) p. 189. [bb] (7) p. 373; (9) pp. 164 and 240. [cc] (7) pp. 371–2; (8) pp. 450–2; (9) p. 277; (11) p. 162. [dd] (8) p. 450; (11) p. 162. [ee] (10) p. 189; (11) p. 99. [ff] (7) p. 372; (11) p. 162. [gg] (7) pp. 371–2; (11) p. 162. [hh] (7) p. 372; (13), (14). [ii] (7) p. 371; (9) pp. 164, 170, 179, 184, 211–12, 238, and 420; (15), (16) and (17). [jj] (7) p. 372; (9) pp. 84, 179, 240; (11) p. 163; (17). [kk] For constructing complexes of Cr^{III}, Fe^{II}, Ni^{II}. [ll] For constructing complexes of Cr^{II}, Fe^{III}, Co^{III}, Cu^{II}, Pt^{II}, Hg^{II}. [mm] For constructing complexes of Mg^{II}, Zn^{II}, Hg^{II}. [nn] Extensive literature references and details on use of the three metal atoms available from author on request.

The additivity of covalent radii thus obtained is such that the over-all dimensional error even in large models, such as of steroids, will seldom be greater than ±0.1 Å. The benzenoid carbon atom was chosen as the standard trigonal carbon atom to which all other values for double-bond lengths were related. This choice introduces a very small error into the length of the ethylene molecule, but allows a single trigonal carbon atom to be used in all cases where some other atom is doubly bound to carbon. Thus the trigonal carbon atom may be used for all aromatic systems, and the small error in ethylene disappears if the double bond is conjugated with any other π-electrons (as in vinyl chloride, styrene, etc.). The triple-bond standard is the acetylenic (digonal) carbon atom. This atom is also used as the central carbon of allenes, and when combined with two trigonal carbon atoms it gives the allene molecule with a total length of 2.60 Å, which compares very well indeed with the experimental value of 2.62 Å.

A special feature of these models is the inclusion of N-tetrahedral, useful in modeling quaternary salts. When fitted with its N-amino cap, it becomes an amino nitrogen with all of the proper dimensions.

It may be noted that the covalent radii of O-digonal, O-carbonyl, and fluorine are a few hundredths of an Ångstrom shorter than the usually accepted values. The radii employed here reflect observed bond-shortening due to the difference in electronegativity between carbon and oxygen, and carbon and fluorine(*4*), and are in accord with the latest microwave data. Because the covalent and van der Waals radii of carbonyl oxygen and nitrile nitrogen are so nearly identical, carbonyl oxygen may be used with virtually no loss of accuracy in place of nitrile nitrogen.

The van der Waals radii reported in the table are the best values reported by Stuart and/or Pauling, and are in general subject to variations of ±0.1 Å. The variations appear to depend upon the environment of the atom in a given molecule, and are accounted for in the present models by the compressibility of the atoms.

Bond angles of 120° were assigned to C- and N-trigonal because this value is most useful in constructing aromatic systems and is quite close to values observed for a large number of other molecules containing C=O, $-NO_2$, C=N, etc. The trigonal nitrogen atom is supplied with a third bond receptacle for the purpose of representing the nitro group and heteroaromatic quaternary compounds.

The bond angles of 105° and 104° were chosen for O- and S-digonal, respectively, because they represent the best compromise from which to construct realistic models. The bond angles in ether-like molecules vary between 95° and 115°, while those in thioethers vary from 90° to about 140°. This variation is largely allowed for by the inherent flexibility of the present models.

Special Features

Hydrogen bonding is effectively represented by inserting Alnico-5 magnets (four are supplied with each set) into slots which may be cut with a pen-knife in the appropriate atoms (such as oxygen, nitrogen, sulfur, and halogens), and pushing thumbtacks into hydrogen atoms with which they are expected to bond. A linear pentamer of water is shown in Figure 2. Such hydrogen bonds are appropriately much weaker than covalent bonds, but are strong enough to hold together carboxylic acid dimers.[4]

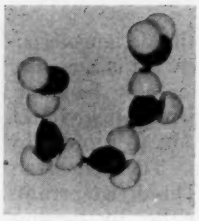

Fig. 2

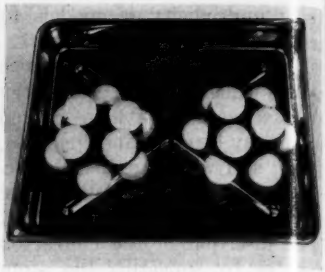

Fig. 3

Figure 2. Hydrogen bonding in water. The chain is actually suspended by two strings.
Figure 3. Boat (left) and chair (right) forms of cyclohexane floating in pan of water.

Sterically favored configurations of highly mobile molecules such as aliphatic and alicyclic compounds, as well as polymers, may be effectively studied by floating the model in a basin of water. Flotation helps to cancel out the effect of gravity on the model and supports it in a manner simulating its natural surroundings. Floating models of boat and chair cyclohexane are shown in Figure 3. Shaking a model in a closed container of water and allowing it to settle will often reveal the conformations which are sterically favored.

The *modes of vibration* which are responsible for infrared spectra are readily demonstrable with these models, and they may be effectively used in teaching the source and usefulness of spectra.

The molding process permanently engraves the demarcation between *covalent* and *van der Waals radii* on all atoms which have valence in only one direction. The distance from the mold-mark to the flat surface is the covalent radius, while the van der Waals radius extends from the mold-mark to the rounded surface, as shown in Figure 1*B*.

Atomic and molecular weights may be demonstrated to elementary students by adding lead shot to an oxygen atom until it is exactly counterpoised on a crude balance by 16 hydrogen atoms. A water molecule is then counterpoised by 18 hydrogen atoms, demonstrating visually the relation between atomic and molecular weight.

Advantage may be taken of the partial thermoplastic nature of polyvinylchloride to *stabilize highly strained structures* such as cyclopropane, if it is desired to subject the model to very rough handling. If the completed model is heated for about five minutes in

[4] If greater hydrogen bond strength is desired, as in the construction of a coiled polypeptide, holes may be bored in the surfaces of hydrogen and, for example, oxygen atoms with a small drill, cork-borer, or heated glass rod. One of the conectors having a tail (Fig. 1*B*) may then be inserted into the larger atom and connected to the hydrogen atom in the usual manner. In this way the author has constructed an alpha-helix of a protein, using carbonyl O and trigonal N for the amide groups, and has found that several turns of the helix are quite stable and possess all of the correct physical measurements in accord with the literature values for H-bond length, pitch of helix, and repeat distance.

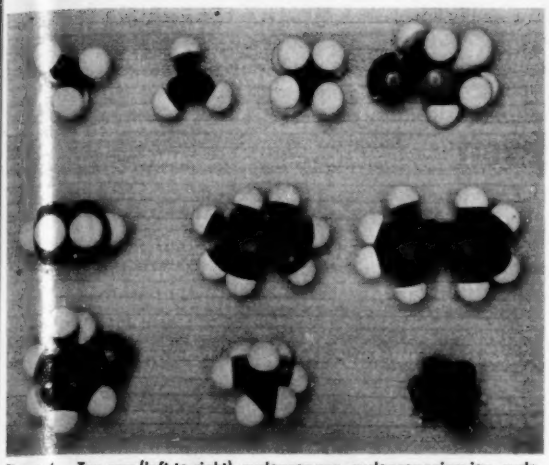

Figure 4. *Top row* (left to right), cyclopropane, cyclopropenium ion, cyclobutane, 4,5-fused ring system of penicillin. *Middle row*, benzene, indole, biphenylene. *Bottom row*, camphor, bicyclo-1,1,1-pentane, diamond.

boiling water or a steam bath, the mechanical strain is largely relieved. On cooling, the atoms are slightly deformed but are under very little tension. When the model is disassembled and the atoms again heated to 100°C, their original shape is restored.

Applications

In addition to the many types of molecules which are more or less satisfactorily represented by other models, the present set may be used to construct realistic models of molecular species which are known to be highly strained. Figure 4, top row, shows cyclopropane, cyclopropenium ion (*5*), cyclobutane, and the 4,5-fused ring structure of penicillin. Figure 4, middle row, illustrates benzene, indole, and biphenylene, the latter compound demonstrating the desirability of being able to model the unknown cyclobutadiene system (*6*). The porphyrin ring system, which is analogous to that of phthalocyanine and is extremely difficult to illustrate with other models, is shown in Figure 5. Bicyclic systems are demonstrated by the models of camphor (minus gem dimethyl groups to reveal ring structure), bicyclo-1,1,1-pentane (unknown),

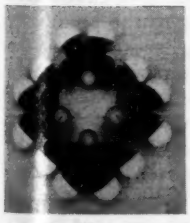

Figure 5

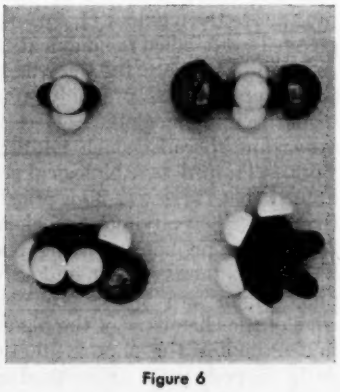

Figure 6

Figure 5. Ring system of porphyrin, minus substituents and central metal atom.

Figure 6. *Top row*, S_N1 and S_N2 transition states. *Bottom row*, (*left*) nucleophylic aromatic substitution transition state; (*right*) benzyne intermediate.

and a fragment of the diamond structure which is identical with the hydrocarbon adamantane and analogous to the structures of hexamethylenetetramine, P_4O_6, and P_4O_{10}, Figure 4, bottom row.

By cutting two extra bond receptacles in the ends of a trigonal carbon atom, the planar transition states of both S_N1 and S_N2 reactions may be illustrated (Fig. 6). Likewise, electrophylic substitution on the aromatic nucleus may be illustrated by replacing one of the trigonal carbon atoms with a C-tetrahedral to which the original proton and the attacking reagent are both attached, showing the charged transition state (Fig. 9). It is then apparent that the intermediate may either collapse to the starting materials, or lose a proton to yield the substituted product.

A number of inorganic structures are shown in Figure 7. It is worth noting that *any* inorganic structure involving nitrogen, phosphorus, oxygen, hydrogen, chlorine, and divalent sulfur may be represented in its covalent form by models now available in this set.

Undoubtedly many other useful variations will occur to the users of this particularly flexible set of atomic models. It is hoped that in the future it will be possible to extend this method of modeling atoms to organometallic compounds and complexes and to the field of crystallography.

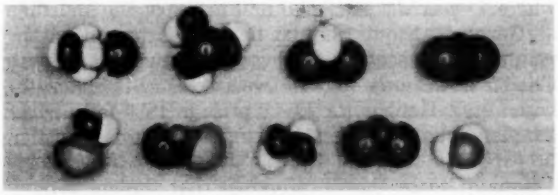

Figure 7. *Top row*, H_3PO_3, H_3PO_4, SO_2, CO_2. *Bottom row*, HOCl, NOCl, H_2O_2, O_3, NH_3.

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Michael Tswett

Everywhere Michael Tswett is credited with being the originator of column adsorption chromatography. However, Zechmeister (*1*) and others have shown that the technique had been used before Tswett, and it therefore seemed desirable to re-evaluate the work of Tswett in order to determine the real importance of his position within the history of science. For biographical details the paper of Dhéré (*2*) is invaluable, as Dhéré had access to personal letters of Tswett and other mementoes not generally available. Nevertheless Dhéré is incorrect about the date of Tswett's death (*3*) and does not attempt a balanced, complete discussion of Tswett's entire scientific output.

Michael Tswett was born at Asti, Italy, on May 19, 1872, the son of a Russian father and an Italian mother. When he was young, the family moved to Switzerland, where Tswett was educated first at Lausanne and then at Geneva. From 1891–96 he was a student in the faculty of sciences at Geneva, studying botany with Chodat and Thury, physics with Soret, and chemistry with Guye. He won the Davy prize in 1894 for a paper on plant anatomy and then under Thury's direction prepared his doctoral thesis, "Etudes de Physiologie Cellulaire." In this he proposed that the chlorophyll pigment is incorporated into a proteinaceous substance called "chloroplastine."

In 1897 he was teaching plant anatomy and physiology in St. Petersburg and doing research on the chemistry of chloroplasts. In 1901 he went to the University of Warsaw as privat-docent, becoming in 1907 professor of botany and agronomy there, and in 1908 professor of botany and microbiology at the Polytechnic Institute in Warsaw. These years in Warsaw produced his most important work until in 1915 the German invasion drove him to Moscow, then to Nizhni Novgorad. In 1917 he went to Vladikavkaz to recover from a serious illness, probably tuberculosis, and then was appointed professor of botany and director of the botanical garden at the University of Dorpat (Estonia). He went there late in 1917, but the German invasion in 1918 again forced him to flee to Russia, where he died at Voronezh on June 26, 1919, at the age of 47.

In his relatively short lifetime, he was allowed only about 15 years of productive, scientific work during which he wrote some forty papers and one book. Of these only about three or four are about strictly botanical subjects although this was the area of his training. The others are very largely of chemical interest and most deal in some way with the plant pigments.

Presented in part at the 132nd Meeting of the American Chemical Society, New York, September, 1957. A fuller discussion of the life and works of Michael Tswett is appearing in *Chymia*, **6** (1959).

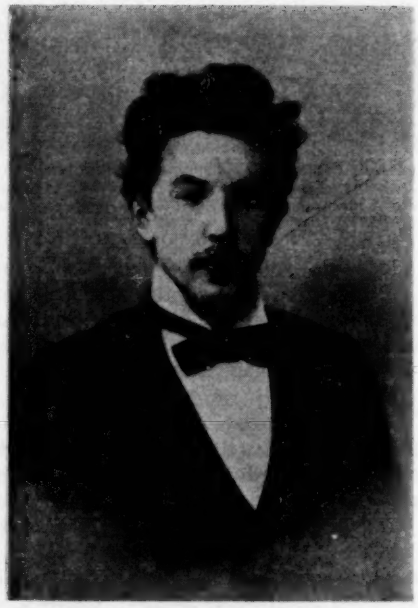

Figure 1. Photograph of Michael Tswett kindly furnished by L. Zechmeister, originally published in *Candollea*, 10, 1943, and reproduced here by permission of the Editor.

Early Researches 1899–1906

Most of the papers of this period already show Tswett's interest in the plant pigments. His belief that native chlorophyll exists as a protein complex led him to attempt the purification of this complex by extraction with resorcinol followed by adding excess water to precipitate the pigment (*4, 5*). By analogy with hemoglobin Tswett called the pigment-protein complex "chloroglobin" and suggested that the binding of chlorophyll to the protein was probably similar to the binding of hematin in hemoglobin. Here one sees one of the important threads which go through all of Tswett's work. Trained as a biological scientist, he constantly argued that there was no a priori reason for supposing that the chlorophyll of the chemists represented the real, native pigment of living plants. This idea goes back to his thesis of 1896 and appears in some form in much of his later work. He pointed out that knowledge of the chemistry of the pigment was of no help in understanding the photosynthetic process and apparently hoped that understanding of photosynthesis could be advanced by obtaining chlorophyll in a more nearly native state.

In 1900 Tswett (*6*) began his series of investigations on the isolation and chemistry of chloroplast pigments

primarily using solvent extraction methods which had been used by others before him. In extracting the pigment Tswett was careful to grind in the presence of calcium carbonate so as to neutralize plant acids which might degrade the pigments. As a result he observed that except for one pigment (carotene) all were adsorbed on the calcium carbonate. This could be washed to remove impurities and finally eluted by using a mixture of light petroleum with 10% alcohol. This fractional adsorption method was applied by Tswett in several investigations (*7*, *8*) and may possibly be a forerunner of the column method used later, although he nowhere indicates that one led to the other.

In 1901 Tswett was ready to state his most important doctrine—the fact that not just one but two green pigments are present in leaves (*7*, *9*). He proposed that the name chlorophyll be applied only to the total mixture and used the names "chlorophyllin α" and "chlorophyllin β" for the individual green pigments. He separated these using the solvent partition methods of Stokes (*10*) and Sorby (*11*) and, in fact, only restated what they had said long before regarding the duality of the pigment, but they had simply been ignored. Tswett was to have to fight vigorously for this idea against some of the leading chemists of his day. In 1901 (*9*) he also stated that the so-called "crystallizable chlorophyll" obtained with long alcohol extraction was actually an artifact formed during the extraction. He called it "metachlorophyllin" by analogy with methemoglobin. We know it today as ethyl chlorophyllide.

In 1905 and 1906 two papers (*8*, *12*) by Tswett appeared describing his researches on pigments of the brown algae. The most valuable result of this work was the discovery of a new substance related to the other two chlorophyll pigments. In his terminology, higher plants contained chlorophyllins α and β, while the brown algae have chlorophyllin α and a new pigment to be called chlorophyllin γ. This is the pigment we now know as chlorophyll *c*, following the work of Strain and Manning (*13*) as recently as 1942, thirty-six years after Tswett's discovery.

Chromatography and the Chlorophyll Pigments

Tswett was deeply interested in the phenomenon of adsorption generally. He not only used it as an analytical tool, he also invoked it to explain certain natural systems. For example, he proposed (*14*) that the chloroplast pigments are adsorbed on the substratum of the granum and this is why nonpolar solvents cannot extract them (except carotene) from leaves although *after* extraction they are soluble in such solvents as benzene or ligroin. The presence of alcohol breaks down the adsorption complex, allowing the pigment to be dissolved. He went so far as to perform model experiments showing that pigment mixtures adsorbed onto various artificial substrata behave just as they do in the leaf with regard to extraction. Then in a paper of 1906 (*14*), after a lengthy discussion of adsorption phenomena, Tswett gives us the first[1] description of his chromatographic method:

> If a petroleum ether chlorophyll solution filters through a column of adsorbent (I use chiefly calcium carbonate which is tightly tamped into a glass tube), the pigments separate themselves from top to bottom in different colored zones according to the adsorption series, in which the more strongly adsorbed substances displace the more weakly held ones farther toward the bottom. This separation is practically complete if one, after the passage of the pigment solution, passes a stream of solvent through the column of adsorbent. Just like the rays of light in the spectrum, so are the different components of a pigment mixture separated in an orderly way in the calcium carbonate column and thus may be qualitatively and also quantitatively determined in this way. Such a preparation I call a chromatogram and the corresponding method, the chromatographic method.
>
> Needless to say, the described adsorption phenomena are suited not only to the chlorophyll pigments. It is to be expected that all kinds of colored or colorless chemical compounds are subject to the same laws.

In another paper (*15*) of the same year he discussed the method in more detail with a diagram of the apparatus used (Fig. 2). Some of his practical advice from this paper is well worth repeating for the instruction of beginning chromatographers today:

> As adsorbent any powdered substance insoluble in the solvent can serve. However, since very many substances are not without chemical influence on the adsorbed material, the choice of the analyst will in general fall to such substances as are chemically inert and at the same time may be most finely powdered. Substances which adsorb too strongly are also to be avoided since they require enormous quantities of pigment in order to make distinctions. Fineness of the adsorbent powder is very important; coarse-grained material produces indistinct chromatograms be-

[1] Poliakov (*3*) states that the first description by Tswett was actually published in Russian in 1903, but I have been unable to obtain this paper.

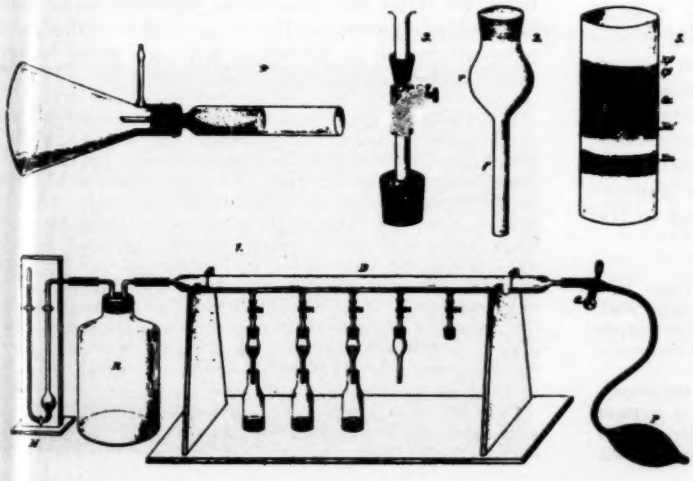

Figure 2. Tswett's chromatographic apparatus. Nos. 2 and 3 are close-up views of the apparatus shown at No. 1 which represents a pressure manifold used for the analysis of several small samples simultaneously. No. 5 gives a close-up of the apparatus shown at No. 4 and indicates zones of separation for the chlorophyll and xanthophyll pigments of leaves.

cause adsorption and diffusion in the too-wide capillary spaces interfere. Among the adsorbents I can frequently recommend precipitated calcium carbonate, which produces the most beautiful chromatograms. Sucrose also may be rather easily brought into the required state of subdivision and offers the greatest guarantee of chemical inertness. For special purposes one will choose chemically reactive adsorbents (for instances, hydrolyzing, reducing, oxidizing).

In the same paper he also described application of the method to pigment analysis, stating that two chlorophyllins, four xanthophylls, and carotene are present in leaves. The second chlorophyll pigment (his chlorophyllin β) was generally believed by the chemists of the day to be either an artifact or present in insignificant amounts. Marchlewski in particular was a leader in this field, and Tswett's contention that chlorophyllin β was a native pigment present in considerable quantity touched off a feud between these two workers which lasted for many years and produced some quite dramatic (and to us today, unbelievable) polemics.

The chemistry of chlorophyll at this time was being studied by the application of various acid and base degradations. Interpretation of these experiments also brought Tswett into conflict with Marchlewski and other leading chemists. Acid treatment of "chlorophyll" clearly yielded two products, "phylloxanthin" and "phyllocyanin." These were thought to represent different stages in the breakdown of the molecule. However to Tswett, who had separated chlorophyll itself into two components, it was evident that one of these products must be formed from his chlorophyllin α and the other from chlorophyllin β. Accordingly he proposed the names chlorophyllan α and β for these compounds (*16*). Using chromatographic separations he showed that it was possible to purify the two chlorophyll pigments first and then convert each one separately to its related derivative or else to convert "chlorophyll" to a mixture of the derivatives and then separate them from each other. The information on acid derivatives was further complicated by the appearance of Willstätter's work in which he gave the name "phaeophytin" to the first acid derivative, ignoring Tswett's work on the duality of chlorophyll.

The objections made by the chemists of Tswett's day seemed to center in an emotional reaction to this new technique of chromatography which seemed to supply answers too easily, bypassing the tedious chemical separations which were familiar. Marchlewski (*17*) complained that Tswett had not put himself to the trouble to isolate and purify the substances he had described, and that one could not with the help of a "filtration experiment" swing himself to the height of a reformer of chlorophyll chemistry. Willstätter argued (*18*) that chromatography was not suitable as a preparative method. Tswett's replies were clear and to the point (*19*, *20*):

> The assertion that my preparations are impure because I have not obtained the pigment in solid form is entirely unjustified. The chlorophyllans were isolated by means of adsorption analysis which is precisely a purification method and in many respects is superior to precipitation or crystallization methods.
>
> It will probably offer no special difficulties to apply the adsorption methods to the preparation of larger quantities of pigment suitable for analysis. One could, for example, as Dr. Werner Magnus kindly suggested to me, use whole batteries of wide adsorption tubes. In any case, adsorption analysis is already now applicable as a powerful control method; and no pigment preparation can be asserted to be a defined, pure substance if it does not show itself as unitary in the chromatographic test also.

In retrospect Marchlewski was right—no one could hope to reform chlorophyll chemistry merely by applying a simple, new-fangled method. Willstätter's beautifully detailed, painstaking applications of standard procedures to kilogram quantities of chlorophyll finally convinced everyone that Tswett had been right all along; or, rather, everyone accepted Willstätter as the founder of chlorophyll chemistry, adopted Willstätter's nomenclature, and forgot that Tswett had said the same things years before—indeed had said them when Willstätter had been arguing the contrary![2]

Tswett's views on chlorophyll chemistry, summarized in 1908 (*21*), are generally quite acceptable today although the nomenclature of Willstätter has replaced that of Tswett.

Other Researches

Returning to 1908, Tswett published in this year two papers (*22*, *23*) on the coloring of autumnal leaves in which he distinguished two phases, the first with the leaf still living, retaining semipermeability, and producing anthocyanin pigments. The second phase involved death of the leaf with concomitant bringing-together of chromogens and enzymes which oxidize them to brown pigments. Using adsorption chromatography, he purified the pigments of yellowed leaves in the first, living, phase and showed that the chief component was not the normal pigment of green leaves merely unmasked by the disappearance of chlorophyll, rather, it was a newly synthesized substance which he named "herbstxanthophyll."

In 1910 Tswett published his only book, "The Chromophylls in the Animal and Vegetable Kingdoms." Unfortunately this was never translated out of Russian, and even the Russian edition is practically unobtainable. In view of Tswett's shorter papers, it seems likely that this may be a treasure trove of valuable observations and insights. The author deeply regrets that he has been unable to see it.

Following this, Tswett published a half dozen short papers on miscellaneous subjects and then, in 1914, his last two papers (*24*, *25*) which are again rather important ones and unfortunately neglected. In these he turns his interest in pigments away from chloroplast pigments to the water-soluble anthocyanin pigments, which he introduces with one of his beautifully illuminating generalizations:

> It is a natural inclination of our spirit to give special notice to anything colored and to want to explain the colored substances in living nature with finality for no other motive. For this reason many *apparent* problems arise. No reason exists to vindicate special physiological or ecological functions for a substance only because it appears tinted to the human eye. Regarded objectively, every substance is indeed "colored," protein, sugar, or water just as much as anthocyanin or chlorophyll. Only, the strongest absorptions of radiant energy lie in another part of the wavelength scale. Now, whether the absorbed color is purposeful (i.e., necessary or required for preservation of the living being) is to be determined empirically in each case. In and of itself, therefore, the subjective coloration has no significance.

[2] The best summary of Willstätter's work is the classic "Untersuchungen über Chlorophyll," R. Willstätter and A. Stoll, Springer Verlag, Berlin, 1913.

The most important part of these papers is that concerned with a discussion of the substances we now call "leucoanthocyanins." Tswett remarked that for many years people had observed certain plant parts to turn red when heated with acid, but apparently he was the first to carry on detailed investigations of this phenomenon. He purified the red pigment and studied its properties, both chemical and physical, concluding it to be very similar to the natural anthocyanins. He also isolated the precursors of the red pigment and showed them to be insoluble in most organic solvents, colloidally soluble in water, and precipitated by egg white. If aldehydes were present during the heating with acid, the pigments that were formed were more violet-red than the pure red ones formed with acid alone. All in all, these compounds seem to have been investigated with great thoroughness by Tswett, and even today it would be possible to initiate some research in this area taking up directly where he left off. However, it is Rosenheim who is generally given the credit for being the first worker to give much attention to leucoanthocyanins on account of his paper (*26*) published in 1920. Rosenheim does deserve credit for proposing the name "leucoanthocyanin," but Tswett's work is fully as detailed and appeared six years earlier.

Conclusion

Whether or not we regard Tswett as the originator of the chromatographic method, it seems clear that he deserves an honored place in the pantheon of science, if not for the discovery of the method, at least for powerful and valuable applications of it as well as for other important discoveries. However, as important as any single discovery was the over-all attitude which Tswett brought to biological chemistry. In contrast to Willstätter, the organic chemist, who said (*27*):

> It was possible without investigating chlorophyll itself, to deduce the peculiarities of its constitution from the consideration of the derivatives which are obtained by the reactions with acid and alkali . . .[3]

we see Tswett's guiding idea (*28*), one which biochemists are only recently coming to appreciate:

> It is too often forgotten, especially on the chemical side, that living tissues are not mere mixtures of compounds remaining in chemical equilibrium, but are organized structures, where, as a result indeed of osmotic boundaries, the most varied reactive bodies stand next to each other and can exercise their mutual chemical potentiality only after the disorganization of protoplasm concomitant with the extraction procedure.

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[3] This is not to disparage Willstätter, whose fine work was of course necessary and of fundamental importance, but only to point out that there was a difference in approach.

Spectrum Analysis, 1859–1959

Tablet on the "Haus zum Riesen" on the Hauptstrasse in Heidelberg. This building formerly was the physics laboratory and is now occupied by the geology department. The tablet reads:

> In this house Kirchhoff applied in 1859 to the sun and stars his spectrum analysis discovered with Bunsen and thus made accessible the chemistry of the universe.

(Photograph by courtesy of Professor Karl Freudenberg, University of Heidelberg.)

Ralph E. Oesper
University of Cincinnati

Condensed Norms: ACS Cooperative Examinations

Two new tests were released in the spring of 1958.[1] The norms have been calculated from the reports, and a condensed version is given below.

The condensed norms are selected from a much larger body of data which can be obtained from the Examinations Committee, American Chemical Society, Theo. A. Ashford, Chairman, 1402 South Grand Boulevard, St. Louis 4, Missouri.

GENERAL CHEMISTRY, FORMS 1958 and 1958-S

Maximum possible score	Q group[a] 100	N-Q group[b] 100	Entire group[c] 100
Percentile rank			
99	85.8	79.4	83.9
95	76.2	65.7	73.2
90	69.9	59.0	66.7
85	66.4	54.8	62.4
80	62.8	51.7	58.9
75	59.6	48.3	55.9
70	57.5	45.2	53.0
65	54.6	42.5	50.5
60	52.2	40.5	48.9
55	49.8	37.7	45.6
50	47.2	35.8	43.2
45	44.8	33.9	40.9
40	42.7	31.9	38.5
35	40.5	29.6	36.0
30	38.3	27.1	33.5
25	35.5	24.8	31.0
20	32.3	21.9	28.1
15	29.3	18.7	24.8
10	25.3	13.7	20.8
5	20.4	8.9	14.2
1	11.9	2.9	5.5

The scoring formula used was R-W/4 throughout.
The figures given are raw scores.

[a] A sample of 1398 papers from 18 institutions was selected from the entire group with fairly common characteristics.
The students were tested at the end of a two-semester course receiving 8 to 10 hours credit, the mean being 9.3. In all schools there were 2 to 3 lecture hours per week, with a mean of 2.9 and from 2 to 6 laboratory hours per week, with a mean of 3.9. Several weeks of qualitative analysis were taught to these students, ranging from 11 to 18 weeks, with a mean of 15.0 weeks.

[b] A sample of 1788 papers from 13 institutions was selected from the entire group with fairly common characteristics.
The students were tested at the end of a two-semester course receiving 8 hours credit. There were 3 to 4 lecture hours given per week, with a mean of 3.1 and 3 to 6 laboratory hours per week, with a mean of 3.6. Little or no qualitative analysis was taught, the range being from 0 to 4 weeks with a mean of 1.1 weeks.

[c] The entire group totaled 4788 students from 40 institutions.
All students were tested at the end of a two-semester course receiving credit varying from 6 to 10 hours with a mean of 8.4 hours. In these schools the lecture hours per week ranged from 2 to 4, the mean being 3.1 and the laboratory hours from 2 to 6, with the mean of 3.7. There was a wide range of total weeks spent on qualitative analysis, ranging from 0 to 18, with a mean of 6.4. The reliability coefficient for the entire group is 0.936, calculated by the Kuder-Richardson Formula No. 21.

[1] Condensed norms for the currently used ACS Cooperative Examinations in J. CHEM. EDUC., **34**, 144 (1957) and **35**, 244 (1958).

ORGANIC CHEMISTRY, FORM 1958

Maximum possible score	Total group[a] 100
Percentile rank	
99	93
95	85
90	77
85	72
80	68
75	64
70	60
65	57
60	54
55	51
50	49
45	46
40	43
35	40
30	37
25	34
20	31
15	26
10	20
5	14
1	7

The scoring formula used was R-W/4 throughout.
All figures given are raw scores.

[a] The norms are based on the scores of 468 students taking a two-semester course in 21 institutions. The group upon which the norms are based is fairly typical and homogeneous, conforming to the following characteristics.
The students received from 8 to 10 hours credit, with a mean of 8.2 hours. The lecture time varied from 2 to 3 hours per week with a mean of 2.7 hours, and the laboratory time per week ranged from 3 to 6 hours with a mean of 4.8 hours. The reliability coefficient for the entire group is 0.958 calculated by the Kuder-Richardson Formula No. 21.

Reviews

General Chemistry, Forms 1958 and 1958S

This examination follows the three-part format of its predecessors, *Forms M* and *K*: Recall of Information (20 minutes, 30 items); Application of Principles (50 minutes, 45 items); and Quantitative Application of Principles (35 minutes, 25 items). Both are of the multiple choice type and are identical except for the sequence of questions and responses, a precaution to discourage copying in crowded classrooms. The 100 items, almost all new, were selected from 400 originally submitted, after screening and pretesting at 31 colleges. The test's comprehensive nature will probably limit its use to a final examination covering the entire general chemistry course. Indirectly, it

indicates what over 60 instructors from varied backgrounds consider important to teach and test in general chemistry.

The current trend from a descriptive to a theoretical approach is reflected throughout the test. Most of the questions, even those under the "Recall" section, require reasoning power. Many "descriptive" questions follow from theory, and a student not exposed to the specific information might still be able to answer from his knowledge of atomic structure and periodic table relationships. However, industrial chemistry has not been neglected.

Of the five equations to be balanced, only one required knowledge of the products, and only one was of the principal net ("ionic") type now in wide use. Additional items might have been included had equation-balancing problems been deleted as separate items and inserted under stoichiometry.

GEORGE B. KAUFFMAN
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Organic Chemistry, Form 1958

Another examination in organic chemistry designated *Form 1958* has been prepared. This test is constructed by a group of teachers from more than 20 colleges under the general direction of a subcommittee headed by B. A. Nelson. It is designed for use as part of a final examination in a full year course in orgaine chemistry.

Composed of 100 questions taking 100 minutes it is much like the other examinations in the series. All questions are multiple choice type with answer sheets provided for either manual or machine scoring. The first 50 questions cover mainly the aliphatic and, the second 50, largely the aromatic divisions. This is a distinct advantage for teachers who may want to test these areas separately. It would also be useful in placing a student whose background courses are not easily determined. In contrast with some former examinations each of these questions has only one correct answer. This feature should avoid the confusion which has been noticed when students took the previous forms.

The questions survey the field as well as any hundred questions could. They cover functional group preparations and reactions, nomenclature, problems of synthesis, proof of structure, and identification, and at least 10% involve the modern concepts and mechanisms. Some teachers may feel there should be some direct questions on laboratory technique.

This 1958 form of the "ACS Cooperative Examination in Organic Chemistry" seems to be a distinct improvement over the other forms and should be carefully considered for use by many teachers.

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R. P. Harpur
McGill University
Macdonald College P. O.,
Quebec, Canada

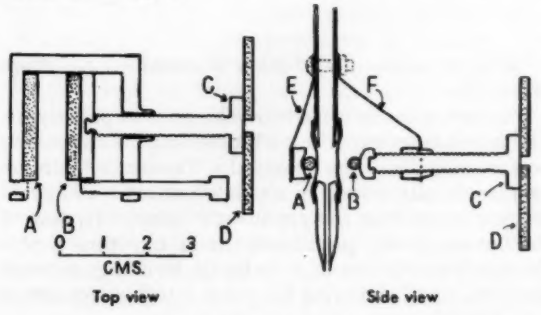
A Simple Valve for Burets or Chromatographic Columns

A recent article by Crawford[1] outlines some of the difficulties encountered when titrating with bases. The control of the flow of chlorinated hydrocarbons through chromatographic columns, especially under pressure, is an even more difficult problem. The commercial valves available are expensive, require special glassware, and some are liable to leak with organic solvents under pressure.

A new form of flexible tetrafluoroethylene tubing (Annealed, Teflon, Pennsylvania Fluorocarbon Co., Inc.), which has recently appeared on the market, may be employed to construct the device described below. When used with a buret it is possible to make titration additions of 0.005 ml, and with chromatographic columns it is easy to control the flow of chloroform under a pressure of 5 lb in.[2] Since tetrafluoroethylene is reported to be resistant to all but molten alkali metals or fluorine at elevated temperatures,[2] this simple valve may find many applications.

The annealed tetrafluoroethylene tubing (4.5 mm i.d.) is pushed as a tight fit over glass tubing and requires no clamps or wire to hold it. Since it is not completely opaque, air bubbles are easily detected. The control mechanism is constructed from a standard hose clamp. Two pieces of No. 8 copper wire (3.3-mm diameter), *A* and *B*, are soldered to the jaws, as shown in the figure. To obtain good alignment it is advisable to solder one wire, *A*, to the stationary jaw, then tin the other jaw and one side of the other wire, *B*, and complete the soldering with the wire *B* clamped lightly in position. A toothed wheel, *D*, from an old alarm clock or toy construction set, is soldered to the knurled knob, *C*, to allow smooth control of the valve.

Although the annealed tetrafluoroethylene tubing is sufficiently rigid to support the weight of the clamp, it is advisable to provide additional support so that the valve may be operated with one hand. This may be accomplished with a small retort clamp or by soldering galvanized iron brackets, *E* and *F*, to the hose clamp as shown in the figure.



Financial support for this project came from the National Research Council of Canada.

[1] CRAWFORD, C. M., J. CHEM. EDUC., **35**, 380 (1958).
[2] *DuPont Bulletin* No. A-6251.

Proceedings of the

Pacific Southwest Association of Chemistry Teachers

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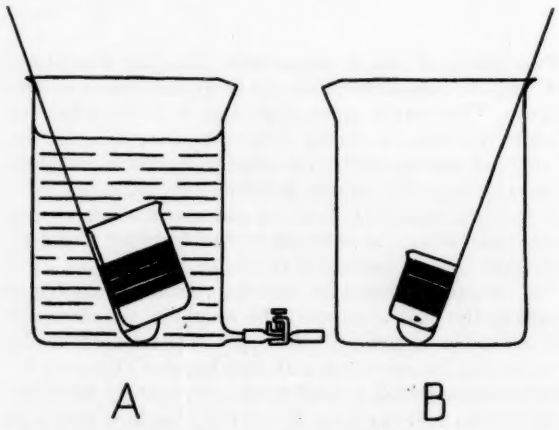
Dynamic Equilibrium

A student demonstration

Before a student is plunged into detailed quantitative calculations involving the specific types of equilibrium constants, it is often useful for him to have a simple qualitative picture of equilibrium in general. The following demonstration has been used for this purpose. The participation and consequent comedy invariably hold the class's attention.

The apparatus consists of two 3-liter beakers, one with a glass outlet tube at the bottom, to which rubber tubing, closed with a clamp, is attached (see figure). The scoops can be conveniently constructed by fastening a large (150-ml) and a small (50-ml) beaker with friction tape to two deflagrating spoons. Beaker *A* is partially filled with water containing a few drops of yellow dye, while empty beaker *B* contains a few drops of blue dye.



Equilibrium apparatus at beginning of demonstration.

The instructor calls for two volunteers to participate. The object is to empty one's beaker into his opponent's beaker using the scoops provided. The participants are to pour simultaneously in a one-to-one ratio and avoid pouring liquid into the opponent's scoop. Tipping of the beakers is not permitted. If at any time a participant is unable to scoop any liquid, he is to go through the motions of emptying his scoop into his opponent's beaker. The other students are asked to predict the outcome, and the contest begins.

At first, student *A* easily scoops his liquid into his opponent's beaker, while student *B*, whose scoop lies above the water level, merely goes through the motions of scooping. As the contest progresses, however, *B* is able to fill his scoop, and soon *A* encounters difficulty in completely filling his large scoop which now projects above the water level. Finally a point is reached at which both participants are withdrawing the same amount of liquid from their beakers. There is consequently no further change in water levels (emphasized by marking the beakers with a grease pencil), and the contest ends in a draw.

The analogy is pointed out between the size of the scoop and the value of the reaction rate constant (k); the larger the scoop, the faster the intrinsic rate of the reaction. The dependence of the actual rates of both forward and reverse reactions upon concentration is shown by the decreasing rate of the forward reaction as the water level in beaker *A* (concentration of reactant) falls, and the increasing rate of the reverse reaction as the water level in beaker *B* (concentration of product) rises. Finally, at equilibrium, the rates become equal. The dynamic nature of this steady state is underscored by the fact that, although there is no net change, both students are busily involved in scooping liquid. The difference between rate of reaction or *how fast* they are scooping (kinetics) and the equilibrium extent of reaction or *how far* they have succeeded in emptying their beakers (thermodynamics) can be pointed out. The dyes are used not only to make the demonstration readily visible at a distance but also to identify the reactant (yellow) and product (blue) and to show by the final uniform green color that both reactants and products are present in the equilibrium system.

The instructor can now intervene and aid student *B* by removing the pinch clamp from the rubber tubing. The equilibrium shifts, and the reverse reaction proceeds toward completion, as student *B* continues to scoop liquid into beaker *A*, while student *A* is unable to return the liquid, which is continually draining from his beaker. This illustrates a general method of forcing a reaction to completion by removing the product. Only the physical limitations of the apparatus prevent student *B* from completely emptying his beaker.

Report of the New England Association of Chemistry Teachers

Official Business

297th Meeting

The 297th meeting of the New England Association of Chemistry Teachers was held at Westbrook Junior College in Portland, Maine, on October 11, 1958. Maurice M. Whitten, Chairman of the Northern Division, served as technical chairman.

The first speaker was Edward T. Bryand, Manager of the New Products Division of Portland Copper and Tank Works. In his talk, "Chemistry as Related to Modern Metal Fabrication," he described various operations where knowledge of the composition of their starting materials was of critical importance. He indicated the broad scope of his company's operations by stating that they "work with all the metals from A to Z, aluminum to zirconium, and no longer produce copper tanks but parts for aircraft, nuclear reactors, and missiles." Of particular interest was the development of brazing alloys for honeycomb structures. The second speaker, Dr. Stanley Herrick, Jr., of the Maine Medical Center and Mercy Hospital, spoke informally of the "Use of Radioactive Isotopes in Medicine" both for diagnostic purposes and for therapy. Specific uses of I^{131}, I^{132}, P^{32} and Co^{60} were reviewed.

In the afternoon Sheldon Cushing of Portland showed beautiful colored slides on "Nature Study" emphasizing close-ups of fungi and other regional flora.

The Chairman of the Membership Committee, Rev. Joseph A. Martus, read the following list of members who have been accepted into the Association since the 1958 Summer Conference:

Rudolph Brada, Regis High School, Denver, Colo.
George E. Crimmins, Randolph High School, Randolph, Mass.
William E. Davis, Bridgton Academy, North Bridgton, Me.
Harris P. Goldberg, Needham High School, Needham, Mass.
Mrs. Virginia B. Isakson, Lyman Hall High School, Wallingford, Conn.
Mrs. Kenneth C. Kruse, Lyman Hall High School, Wallingford, Conn.
Burton R. Norton, Washington State Teachers College, Machias, Me.
Timothy J. O'Connor, St. Joseph's College, North Windham, Me.
Gardner C. Pope, Falmouth High School, Cumberland Center, Me.
Sister Agnes Francis, St. Mary's Central Catholic High School, Milford, Mass.
Sister Miriam Dolores, Elizabeth Seton School, Yonkers, N. Y.
Sister M. Andrene, Cathedral High School, Boston, Mass.

Miss Angela M. Trovato of Branford High School, Branford, Connecticut, was named by President Robert D. Eddy to be Assistant Editor of the *Newsletter*, to succeed Mahlon F. Hayden.

298th Meeting

The 298th meeting was held at Simmons College, Boston, December 6, 1958, jointly with the Eastern Association of Physics Teachers and the New England Biological Association. Dr. John A. Timm, Director, School of Science, Simmons College, welcomed the three science societies in the name of President Park and Simmons College. Richard M. Whitney, Chairman, Central Division, NEACT, then introduced the first speaker of a a panel which had been arranged on the general topic of *ultrasonics*. Dr. Thedor F. Hueter, Acoustics Manager of the Sonar Department of the Raytheon Manufacturing Company, Wayland, Massachusetts, spoke on the physical aspects of ultrasound, outlining the means of propagation and some of the theory and applications to which ultrasonics have been put. By the use of slides he presented the power of this device as a tool in fundamental research in many varied scientific fields. Dr. Eugene Bell, Assistant Professor of Biology at the Massachusetts Institute of Technology, then spoke on the biological aspects of the topic, with emphasis on current research in embryology using ultrasonics as a means for the separation of the ectodermal cell layer from the mesodermal layer of frog and chick embryos. Dr. Alan Hodge, Research Associate in the Department of Biology at Massachusetts Institute of Technology, used the collagen macromolecule for a discussion of some of the chemical uses of ultrasonic radiation. His work on the degradation and analysis of the macromolecule structure with the assistance of ultrasonics gave insight into this sub-branch of science. Dr. H. Thomas Ballantine, Associate Visiting Neurosurgeon at the Massachusetts General Hospital, then presented a discussion of the medical uses of ultrasound, especially in brain surgery. The ability to focus ultrasonic waves has enabled doctors to perform surgery in the center of the brain without damage to the peripheral areas. Dr. Ballantine also demonstrated the use of a small ultrasonic generator as a possible classroom project.

After a luncheon in the Simmons dining hall and the business meetings of the individual societies, the afternoon joint meeting was given over to the presentation of the motion picture film, "Principle of Ultrasonics," from the British Information Service, and to a panel discussion and question period on ultrasonics. The members of the audience had been requested to write out questions, and these were then answered by the morning speakers. The meeting closed with further demonstration on the part of Dr. Ballantine of the ultrasonic generator which he felt could probably be borrowed from some physician in almost any town. Although such apparatus is of relatively low frequence and intensity, several demonstrations can be given to illustrate some of the properties of such high frequency sound.

The following were admitted as members of the Association at this meeting:

J. Gordon Annett, Hackensack High School, Hackensack, N. J.
Clarence D. Berger, Staples High School, Westport, Conn.
Brother Alfred Peter, F. S. C., De LaSalle Academy, Newport, R. I.
Brother C. Joseph, F.S.C., LaSalle Military Academy, Oakdale, Long Island, N. Y.
Brother Ivo, C.F.X., St. John's Preparatory School, Danvers, Mass.
Anthony Carcieri, Coventry High School, Coventry, R. I.
Walter G. Congdon, Mt. Hermon School, Mt. Hermon, Mass.
Lloyd S. Dale, West Springfield High School, West Springfield, Mass.
Peter H. Debevoise, South Portland High School, South Portland, Me.
Robert Dolloff, Foxboro High School, Foxboro, Mass.
Horton K. Durfee, Darrow School, New Lebanon, N. Y.
Bernard Gollis, Bedford High School, Bedford, Mass.
Donald B. Hilton, University of Maine at Portland, Me.
Rev. Alvin Hufnagel, S. J., Brooklyn Preparatory School, Brooklyn, N. Y.
Graham Jones, Student, Tufts University, Medford, Mass.
Donald H. Kay, Massachusetts College of Pharmacy, Boston, Mass.
Daniel H. Kehoe, Quincy High School, Quincy, Mass.
Donald G. Klim, Greenwich High School, Greenwich, Conn.
Alan Lander, Avon High School, Avon, Mass.
Edward F. LaSala, Massachusetts College of Pharmacy, Boston, Mass.
Walter J. Palasita, Ferris High School, Jersey City, N. J.
David W. Parfitt, Brookline High School, Brookline, Mass.
Eleanor M. Peck, Winchester High School, Winchester, Mass.
Janet S. Perkins, Simmons College, Boston, Mass.
Margaret F. Polglase, Glastonbury High School, Glastonbury, Conn.
Ernest C. Shawcross, The Pingry School, Hillside, N. J.
Sister Mary Timothy, R.S.M., St. Ann High School, Gloucester, Mass.
Carleton P. Stinchfield, Norton Co., Worcester, Mass.
Edward J. Sullivan, Leicester High School, Leicester, Mass.
Everett A. Trousdale, Naselle High School, Naselle, Wash.
T. J. Tuori, Great Neck North Senior High School, N. Y.
George A. Weygand, Bridgewater State Teachers College, Bridgewater, Mass.
Mrs. Rachel K. Winer, Holliston High School, Holliston, Mass.
Roger W. Woodhead, Oyster River High School, Durham, N. H.
Robert H. Zaim, Massachusetts College of Pharmacy, Boston, Mass.

Necrology

The Necrology Committee reports with regret the death of the following members:

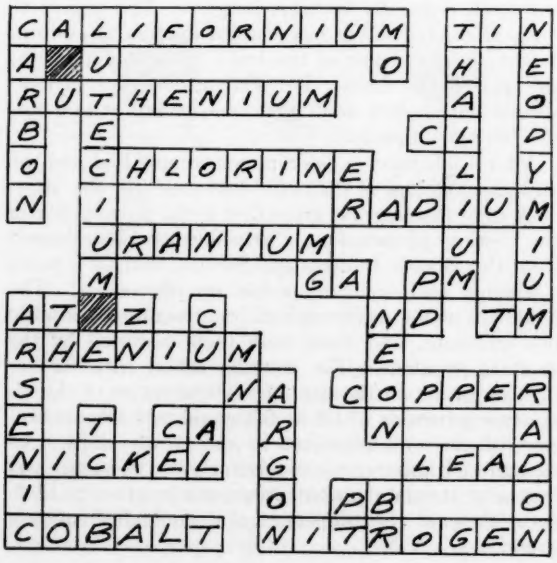
Ernest Dana Wilson, Worcester Polytechnic Institute, October 19, 1958.
Rev. Michael A. Leonard, S.J., Campion College, Regina, Saskatchewan, Canada, June 27, 1958.

Announcement of 300th Meeting

On Saturday, April 11, 1959, a joint meeting of NEACT with the Connecticut Valley Section of the American Chemical Society will be held at the High School, Hamden, Connecticut. Harry Sisler of University of Florida will be the principal speaker. Visitors to New England for the Boston meeting will be most welcome.

Laurence S. Foster
Editor of NEACT REPORT

Solution to Skeleton Puzzle (February)



Chem Ed

LETTERS

To the Editor:

The committee report of the Division of Chemical Education on Institutes has recently been circulated and, as well, published in this Journal. The program offered at the University of Minnesota for the eight-weeks period from June 15 to August 7 was omitted in both instances. The reason given for the omission was that three fields—chemistry, physics, and mathematics—were being offered and the committee was reporting only on Institutes with chemistry and one other field. In effect, the registrant at the Minnesota Institute can take chemistry and only one other area. Thus our program should have been included in the advertising. It is further noted that the committee, in their recently circulated report, stated a need for a program which combined only chemistry and mathematics. We feel that our Minnesota program fills exactly that need.

Robert C. Brasted

University of Minnesota
Minneapolis 14

Chem Ed

BOOK REVIEWS

An Introduction to Chemistry

Charles Compton, Professor of Chemistry. Williams College. D. Van Nostrand Co., Inc., Princeton, N. J., 1958. xiv + 607 pp. Many figs. and tables. 16 × 23.5 cm. $6.85.

The author has made a conscious effort to utilize the traditional general chemistry approach and the trend toward the "physical chemistry" development in freshman chemistry in this text which was developed primarily for a one year terminal course for nonmajors.

Evidences of some success in correlating these different viewpoints is apparent in the first three chapters. Here the "traditional" is emphasized by using the case history technique in considering the concept of matter, the theory of combustion, and the development of the atomic theory. The use of specific examples and the identifying of fact and of generalization permits the student to recognize how different postulates were suggested, tried and used or dropped as experimental evidence demanded.

Such an introduction leads very naturally to the consideration of the structure of matter as the general topic covered in the first eight chapters.

Chapter 7 on "interunit forces" calls to the student's attention some important relationships between physical properties and atomic structure. Nuclear chemical changes are introduced in Chapter 9.

The author presents a very considerable amount of information in table form throughout the book. One table, "The Formulas and Some Properties of a Number of Common Compounds," occupies twenty-one pages giving the color, state, electronic structure, and formula of 113 common compounds.

The most unique, interesting, and important contribution, in this reviewer's opinion, that the book makes to chemical education is found in the chapters headed, "The Nature of Discoveries in Chemistry" and "The Conditions for Discovery." Dr. Compton discusses briefly but clearly the techniques, the methods and the arts involved in scientific problem solving. He identifies the difficulties of communicating new ideas, the cumulative, chain reaction nature of science, as well as its values and its limitations.

A considerable space is devoted to laboratory techniques; to "technology"; to foods, medicine, plastics, etc. Perhaps this is justifiable if these students become aware of chemistry's contribution to our world.

Questions at the end of the chapters require, for the most part, some good thinking and synthesis rather than the memorizing of miscellaneous facts. The supplementary reading lists are well chosen and not too technical for these students.

"An Introduction to Chemistry" is an interesting attempt to meet the needs of the nonscience major, well written and with very few errors. The author has included various chemical problems but has minimized the chemical arithmetic which causes many nonscience majors to abhor the field. Common experiences and conditions are used to illustrate his discussions rather than unknown hypothetical situations.

The only real problem that this volume presents is a very common one for the general chemistry instructor; with such a wealth of suggestions and ideas the difficulty is deciding what one can conscientiously leave out of the course.

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Reviewed in this Issue

Charles Compton, An Introduction to Chemistry
Samuel Glasstone, Sourcebook on Atomic Energy
Frederick T. Wall, Chemical Thermodynamics
Brian Mason, Principles of Geochemistry
Brother Joseph McCabe and *W. W. Eckenfelder, Jr.*, Editors, Biological Treatment of Sewage and Industrial Wastes. Volume 2: Anaerobic Digestion and Solids-Liquids Separation
Robert C. Reid and *Thomas K. Sherwood*, The Properties of Gases and Liquids
Soviet Pharmaceutical Research
George Norwitz, Rapid Analysis of Nonferrous Metals and Alloys
O. Kubaschewski and *E. LL. Evans*, Metallurgical Thermochemistry
Paul Pascal, Editor, Nouveau Traité de Chimie Minérale, Volume 12
Maurice L. Huggins, Physical Chemistry of High Polymers
Paul Pascal, Editor, Nouveau Traité de Chimie Minérale, Volume 19

Sourcebook on Atomic Energy

Samuel Glasstone, Consultant to the United States Atomic Energy Commission. 2nd ed. D. Van Nostrand Co., Inc., Princeton, N. J., 1958. 641 pp. Many figs. 16 × 23.5 cm. $4.40.

About 50,000 copies of the first English language edition (THIS JOURNAL, 28, 342 (June, 1951) of this sourcebook were sold and the book was translated into several foreign languages. A page-by-page comparison of the second edition with the first shows the extent of the revision. For the most part the writing is identical with the first edition except for the interpolation of new material, with a resulting addition of about 100 new pages. Some obsolete data have been replaced by new, but the revision has consisted mostly of a skillful insertion of new material to bring the sourcebook up to date, as of January, 1958.

Some details will aid the teacher to decide whether he will wish to replace his first edition by purchasing a copy of the second. In Chapter II, Fundamental Particles, a new section has been added on the antiproton, with a clear description of the experiments used in evidence of their existence. A new section has similarly been inserted on the antineutron, but neutrinos are not mentioned until Chapter VII. The tables on radioactive series have been corrected by insertion of new values for half-lives, etc., and the section on Ionization Instruments has been rewritten. The time-of-flight mass spectrometer is now discussed, as well as the nozzle method of separating isotopes. The section on the separation of deuterium has been enlarged. The discussion of charged particle accelerators has been augmented by new material on the alternating gradient synchrotron and by a discussion of the acceleration of heavy ions. The section on Transmutation by Heavy Ions is new, as well as the section on Transmutation by Radiation and by Electrons. There has been added a new section on Meson Theory of Nucleon Forces. Under properties of nuclei, new material has been inserted on Nuclear Magnetic Moments and on Magnetic Quadripole Moments. There is an enlarged discussion of the Nuclear Shell Model and of Magic Numbers. The discussion of Fusion has been increased from three pages to nine. The biggest change has been the addition of a new chapter on Nuclear Reactors, in which the original eleven pages on this topic have been increased to 32. The section on Uses of Isotopes has been considerably enlarged and is now titled Uses of Isotopes and Radiations. The chapter on Cosmic Rays and Mesons has been retitled, Cosmic Rays and Strange Particles, with appropriate additions of new material. The last chapter on Radiation Protection and Health Physics has been increased in scope. The RAD unit has been correctly introduced in place of older ones.

From the brief notes given in the previous paragraph, the scope of the sourcebook is apparent and it must also be obvious that no teacher of science today can afford to be ignorant of the new field

of "atomic energy" or to ignore its social implications. It is hoped that this very competent second edition will be even more popular than the first.

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Chemical Thermodynamics

Frederick T. Wall, University of Illinois. W. H. Freeman & Co., San Francisco, 1958. vii + 422 pp. 16 × 24 cm. $8.

This book is meant to be a textbook for graduate students or advanced undergraduate students in chemistry (it is not a treatise for experts). For this purpose, the reviewer feels that it is not only an excellent work but is, indeed, the best available at the present time. For example, Lewis and Randall is out of date; MacDougall is out of print; Klotz is a little too classical and overemphasizes numerical work somewhat; and Guggenheim is too advanced for most beginners (though it would be the book of choice for a class consisting of potential theoretical chemists). Wall presents a nice balance between theoretical and applied thermodynamics, and at the right level for the average chemistry graduate student. The problems are especially refreshing—departing in many cases from the usual exercises in numerical manipulation.

An elementary presentation of statistical mechanics is interspersed with the thermodynamics. This is becoming more popular, at least in books. The reviewer prefers in lectures, at least, to treat thermodynamics and statistical mechanics as separate courses, though an indispensable part of the thermodynamics course would be a molecular interpretation, *in words*, of as much thermodynamic data and as many equations as possible. Fortunately, the statistical mechanics in Wall's book can be omitted at the instructor's option.

The reviewer finds one very annoying feature: following Lewis and Randall, Wall sees fit to use the partial molal Gibbs free energy symbol ($\bar{F}_i$) instead of the chemical potential symbol (μ_i). This is unfortunate for two reasons: (*a*) the chemical potential plays a very special and important role (along with pressure and temperature) in determining phase and chemical equilibria and so deserves a special symbol; and (*b*) the chemical potential is related mathematically (as a differential coefficient) not only to F, but also to A, E, and H. Wall's choice in this matter is especially surprising in a book which includes some statistical mechanics, since statistical mechanicians almost always use μ_i.

Professor Wall, as a textbook writer, has the advantage of being, in his own research, a skilled practitioner of both statistical mechanics and thermodynamics. This advantage is not only evident throughout the book, but is perhaps its most obvious feature.

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Principles of Geochemistry

Brian Mason, Professor of Mineralogy, Columbia University. Second edition. John Wiley & Sons, Inc., New York, 1958. vii + 310 pp. 48 figs. 44 tables. 15.5 × 23.5 cm. $8.50.

This book is suitable for a one-semester course in geochemistry aimed principally at geologists, and emphasizing areas where chemical principles are applicable. The approach to all subjects is that of the geologist and the chemical principles used are mostly of an elementary nature. A chemist might have difficulty deducing that $KAlSi_3O_8$(Or) is orthoclase since it is not clearly indentified in the text, p. 102. The chapter on Thermodynamics and Crystal Chemistry is somewhat hazy from the viewpoint of a chemist. Thus the statement on p. 65, "it is the change in internal energy which the system undergoes in passing from one state to another that is significant," needs considerable amplification. The citing of Le Chatelier's principle, p. 67, might arouse J. de Heer (THIS JOURNAL, **34**, 375 (1957)). The statement on p. 210, "*no* loss of gases into interplanetary space should have taken place since the earth cooled to its present temperature, because even for hydrogen the mean square velocity is considerably less than the velocity of escape," needs qualification. The normal distribution of velocities would allow *some* molecules to have velocities equal to the escape velocity.

The material in the text has been brought up to date since the first edition in many ways. For example, the astronomical age of the universe has been revised and more data on geologic dating has been added. The description of the makeup of the crust above the Mohorovicic discontinuity has been changed to conform to more recent seismic work. The type has been enlarged to more readable size in most tables.

Since the first edition of this book was published, interest in the field of geochemistry has increased markedly. The Geochemical Society was formed in 1955 and has over 1500 members. As a textbook in this special field, giving a rapid over-all picture of the field, this book should be useful. As a general reference book in the field, one should rather consult Goldschmidt or Rankama and Sahama. No exercises or problems are included in Mason's book.

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Biological Treatment of Sewage and Industrial Wastes. Volume 2: Anaerobic Digestion and Solids-Liquids Separation

Edited by *Brother Joseph McCabe* and *W. W. Eckenfelder, Jr.*, Manhattan College. Reinhold Publishing Corp., New York, 1958. vi + 330 pp. Many figs. and tables. 15 × 23 cm. $11.50.

The text contains the papers presented at the Conference on Anaerobic Digestion and Solids Handling held at Manhattan College in April, 1957, and is a companion volume to Volume 1, "Aerobic Oxidation." The book is divided in three parts: Part I, Anaerobic Treatment (14 papers), Part II, Sedimentation and Flotation (10 papers), and Part III, Vacuum Filtration and Sludge Conditioning (4 papers). Each paper is followed by a list of references. An author index and a subject index appear at the end of Part III.

Each paper is well written, and accompanying figures and tables are easily understood. The book is not for the layman but is intended for those who have a strong background in wastes treatments and problems and who wish in one volume to acquaint themselves with recent advances in these areas. Representative paper titles are as follows: Anaerobic Digestion of Pulp and Paper Wastes, The Uniflow Tank—An Improved Settling Tank, and Sludge Elutriation.

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The Properties of Gases and Liquids

Robert C. Reid, Assistant Professor of Chemical Engineering, and *Thomas K. Sherwood*, Professor of Chemical Engineering, both of Massachusetts Institute of Technology. McGraw-Hill Book Co., Inc., New York, 1958. xii + 386 pp. Many figs. and tables. 16 × 23.5 cm. $10.

Not enough physical data on the new compound to design a plant to make it? Don't say it can't be done! Estimate the properties from equations and rules given by Reid and Sherwood.

The physical chemist likes to work with thermodynamically exact equations to calculate unknown properties from experimental data. The Clapeyron equation is an exact equation. The chemical engineer will make approximations to put this equation in a form that can be used with the data available. The Clausius-Clapeyron equation and graphical methods, as the Othmer plot, are approximations from the exact equations.

Reid and Sherwood have selected a number of important properties of gases and liquids and have given the better equations to calculate approximately the values of these properties. The properties, given by chapters, are: critical properties; P-V-T properties; vapor pressures and latent heats; heats, free energies of formation, and heat capacities; viscosity; thermal conductivity; diffusion coefficients; vapor-liquid equilibria. A number of methods are given, starting with one which requires the least data and continuing to the more complex, but accurate, equation. Tables are given which show the percentage deviation of values calculated by several equations from the experimental values. Finally a recommendation is made as to the equation to be used with the data available.

No mention has been made of the excellent series of articles on "Estimate Engineering Properties" by W. R. Gambill

(*Continued on page A166*)